# A DECISION ANALYSIS APPLICATION: PATROL FRIGATE TEST AND EVALUATION AT LAND BASED TEST SITES

Kenneth Harper Kerns

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# THESIS

A DECISION ANALYSIS APPLICATION:
PATROL FRIGATE TEST AND EVALUATION
AT LAND BASED TEST SITES

by

Kenneth Harper Kerns

September 1974

Thesis Advisor: W. C. Giauque

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# A Decision Analysis Application: Patrol Frigate Test and Evaluation at Land Based Test Sites

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Lieutenant Commander, United States Navy
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TABLE OF CONTENTS

## LIST OF TABLES

LIST OF DRAWINGS

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# I. INTRODUCTION

There is general recognition in the armed services that the management of projects concerned with weapons systems development and production is an increasingly complex and important task. The development and procurement costs of major weapons systems have steadily increased over the past ten years [Ref. 1]. Additionally, a need to reduce Department of Defense (DOD) spending has been identified many times by the President and other government officials as well as concerned citizens. These problems are placing an increasing burden on project management. The existence of cost and schedule over-runs and performance, maintainability, and reliability problems with the final weapons system hardware indicates there is room for improvement.

There are several areas in project management where formal analysis can be of potential benefit to the project manager, to the Navy and to the researcher. One such area concerns how trade-off decisions are made among various factors such as cost, performance, and schedule. A good manager must have the ability to make reasonable judgments in these areas. He must determine the realizable alternatives and then select that alternative which best satisfies the overall objectives of the project. These judgments must often be made in highly uncertain environments.

An approach to aid the manager in trade-off decisions, not typically used in the past, is the use of decision analysis. Decision analysis is a systematic procedure to

logically describe, specify and balance all factors which affect a decision. Among the factors considered in decision analysis is the probability that a specific outcome will occur from the various possible consequences. The preferred alternative also depends on the decision-maker's preferences for those consequences. The techniques used in decision analysis may enable a project manager to break a relatively complex judgmental situation down to a series of simple decisions.

## A. PURPOSES

The purposes of this thesis were fourfold. The first purpose was to demonstrate that decision analysis techniques can be used as a project management tool. The second purpose was to provide the author with experience in conducting decision analysis in the project management environment. This was particularly useful because the research contained cases of multidimensional consequences under uncertainty. The third purpose was to provide examples of project management decision problems which could be incorporated into the United States Naval Postgraduate School's Adminstrative Science Curriculum. The forth purpose was to generate interest in the use of decision analysis in project management decision-making.

## B. LAND BASED TEST SITE TRADE-OFFS

A current example of project management trade-off decision making is the problem of what constitutes an optimum mix of actual and simulated subsystems of the Patrol Frigate (PF) escort vessel which would be installed and tested at a land based test site. The testing must be satisfactory for PF production approval by the Defense

System Acquisition Review Council (DSARC). Consequently three subsystems of the Patrol Frigate, the AN/SPS-49 radar, the Mark 92 mod 2 Fire Control System (FCS), and the LM 2500 gas turbine engine, were selected as examples of how decision analysis can be demonstrated in this thesis. Four alternatives were considered. They are

(1) installation of the actual equipment,

(2) installation of some actual and some simulated equipment,

(3) installation of entirely simulated equipment, or

(4) no installation necessary at the land based test site.

## C. LIMITATIONS

There are some limitations to this thesis. It was written in the decision environment of the project manager. External influences such as political, social and cultural factors were not included. Some generalizations were made in order to maintain this thesis unclassified. Cost and schedule parameters represent an order of magnitude and are the results of experienced judgments of personnel from the PF Ships Acquisition Project Office (PMS-399) located at the Naval Sea Systems Command Headquarters. A set of utility functions was developed for one individual concerned with the problem to illustrate the method and use of decision analysis. Finally, the preferences for consequences and the assessments of judgmental probabilities were provided by personnel in the PF Project Office. No refinements were made on these assessments from other sources.

## D. THESIS ORGANIZATION

this thesis is organized in the following manner. Chapter II presents a background of the Patrol Frigate Land Based Test Sites (LBTS). Decision analysis methodology is explained in Chapter III. This explanation includes discussion of the systematic steps used in formal decision analysis and the evaluation of multidimensional consequences under uncertainty. Formulation of the decision analysis procedures used in deciding the alternative that best satisfies the objectives of LBTS testing for the three PF subsystems under consideration is described in Chapter IV. Chapter V provides the solution procedures and the recommended courses of action. Chapter VI summarizes the thesis, presents recommendations and provides suggestions for further research.

# II. BACKGROUND

On 13 July 1971, Deputy Secretary of Defense David Packard created a major change in the DOD management of major defense system acquisitions with the issuance of Department of Defense Directive 5000.1. The Directive, titled "Acquisition of Major Defense Systems," applies to programs designated as major by the Secretary or Deputy Secretary of Defense. This Directive recognizes that sucessful development, production and deployment of major defense systems are dependent on people, priorities and clearly defined responsibility. To this end, the policy invoked by this document designates the program manager as the key individual accountable for a major acquisition program. He should have a charter with sufficient authority to accomplish his program objectives and sufficient tenure to accomplish his task. The layers of management between the program manager and his service should be minimized [Ref. 2].

## A. PF PROJECT

If a program results in an expenditure in excess of 50 million dollars for research and development, or is in excess of 200 million dollars during production or is urgent to National Security it will be classified as a major acquisition program. The Patrol Frigate Project has been classified in this category.

1. Objective

The objective of the PF Project is to acquire by the late 1970's a class of ships which will provide, at least cost, the maximum improvement in the Navy's surface combatant capability to defend non-carrier forces against airborne and sub-surface attacks.

The PF is an austere escort ship designed to provide maximum mission capability within the constraints of average follow ship cost of 47.7 million dollars (FY 73 dollars), a full load displacement not exceeding 3500 tons and total personnel accomodations not exceeding 185. Follow ship cost is defined to mean the unit production cost of ships built after construction of the lead ship.

2. The DSARC Review Process

There are four life cycle phases for a normal weapon system acquisition program. The first phase is the conceptual phase. The objective of this phase is to define the operational need. The system concepts which warrant development are explored. The second phase is the validation phase in which alternative system concepts are validated as a basis for determining whether or not to proceed into full-scale development. The third phase is full-scale development. The objective of this phase is to design the system, construct a full-scale prototype for test and evaluation and provide the documentation needed to produce the system. The final phase is the production phase in which the system is produced for operational use. Before one phase is permitted to proceed into the next phase, approval must be obtained from the Defense System Acquisition Review Council.

The DSARC review process occurs at three decision point milestones during the normal life cycle of the system development. These points in time are defined as

(a) DSARC I, which occurs between the conceptual and validation phase,

(b) DSARC II, which occurs between the validation and the full-scale development phase and

(c) DSARC III, which occurs between the full-scale development and production phase.

Before a project can sucessfully pass the three DSARC decisions, it must be increasingly better defined and have minimized the technical uncertainty and program risks. Test and evaluation, to the extent it can be performed in each phase, is an important means for reducing such risk and uncertainty.

### 3. Test and Evaluation

Department of Defense Directive 5000.3 [Ref. 3] establishes the policy for the conduct of test and evaluation by the DOD components in the acquisition of defense systems. The general policy is that test and evaluation shall be commenced as early as possible and conducted throughout the acquisition cycle to assist in progressively reducing risks and assessing military worth.

The Directive defines Development Test and Evaluation (DT&E) as the test and evaluation conducted to demonstrate that the engineering design and development process is complete and that the design risks have been minimized. DT&E commences as early in the development phase

as possible after DSARC II to demonstrate that technical risks have been identified and that solutions are in hand. Prior to DSARC III, the DT&E accomplished should ensure that the engineering is essentially complete and that all significant design problems have been identified and have solutions.

Operational Test and Evaluation (OT&E) is conducted to evaluate the developed system's operational effectiveness. The Directive specifies that acquisition programs will be structured so that at least an initial phase of Operational Test and Evaluation (IOT&E) will be accomplished prior to DSARC III adequate to provide a valid estimate of the expected system operational effectiveness and suitability.

Department of Defense Directive 5000.3 further adds:

> "The long, design, engineering, and construction period of a major ship will normally preclude completion of the lead ship and accomplishment of test therefore prior to the decision to proceed with follow ships. In lieu thereof, sucessive phases of Development Test and Evaluation (DT&E) and Operational Test and Evaluation (OT&E) will be accomplished as early as practicable at test installations and on the lead ship so as to rapidly reduce risks and thereby minimize the need for modification to follow ships."

4. PF Land Based Test Site Rationale

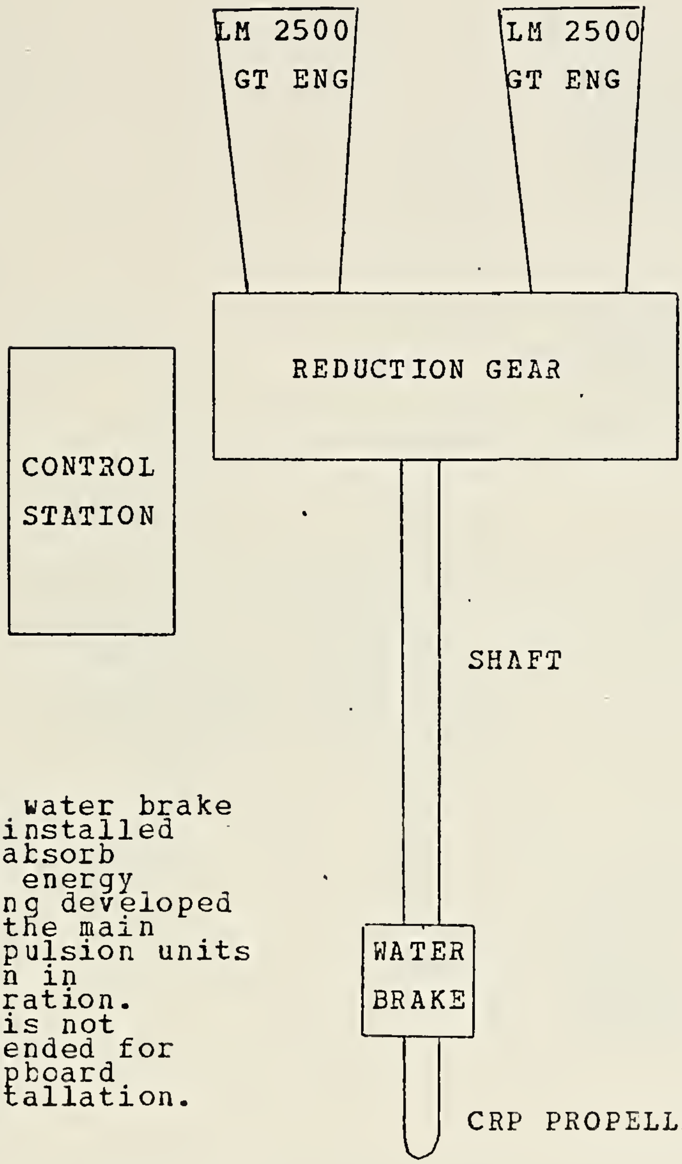
The DSARC II review for the Patrol Frigate Program was held on 31 August 1972. The Deputy Secretary of Defense issued a Decision Memorandum for the Secretary of the Navy. In this Memorandum, one of the decisions reached by the Deputy Secretary of Defense was that approval of follow ship production should be contingent upon adequate test and evaluation individually on subsystems and collectively at land based test sites [Ref. 4]. In order to satisfy the requirements contained in Refs. 2 - 4 described above, the

Project Manager has determined that the propulsion and combat systems for the Patrol Frigate should be prototyped at land based test sites (LBTS).

The Propulsion System LBTS is now under construction at the Naval Shipyard in Philadelphia, Pennsylvania. The LBTS will consist of two LM 2500 gas turbine engines, one reduction gear complete with high speed clutches and brakes, one controllable reversible pitch propeller hub with dummy blades, one shaft, a control system and a control station. Figure 1 illustrates the Propulsion system arrangement.

The Combat System LBTS, is located at MacArthur Field, Long Island, New York. Actual equipment to be installed consist of one AN/SPS-49 air search radar, one AN/SPS-55 surface search radar, a Mark 92 mod 2 Fire Control System, two AN/UYK-7 computers used as Weapons Control and Support Processors and miscellaneous switchboards and communications equipment. Functional simulators will be provided for the missiles, launchers, gun mounts, sonar and electronics countermeasure equipment [Ref. 5]. Figure 2 illustrates a block diagram arrangement of the Combat System LBTS. It is to be noted that the location of the Combat System LBTS is five miles from the coast line, surrounded by trees and dwellings. This will limit low flying aircraft operations and prohibit the actual firings of guns or missiles [Ref. 6].

PF PROPULSION SYSTEM LBTS EQUIPMENT CONFIGURATION




Note: The water brake is installed to absorb the energy being developed by the main propulsion units when in operation. It is not intended for shipboard installation.

FIGURE 1

PF COMBAT SYSTEM LBTS EQUIPMENT CONFIGURATION

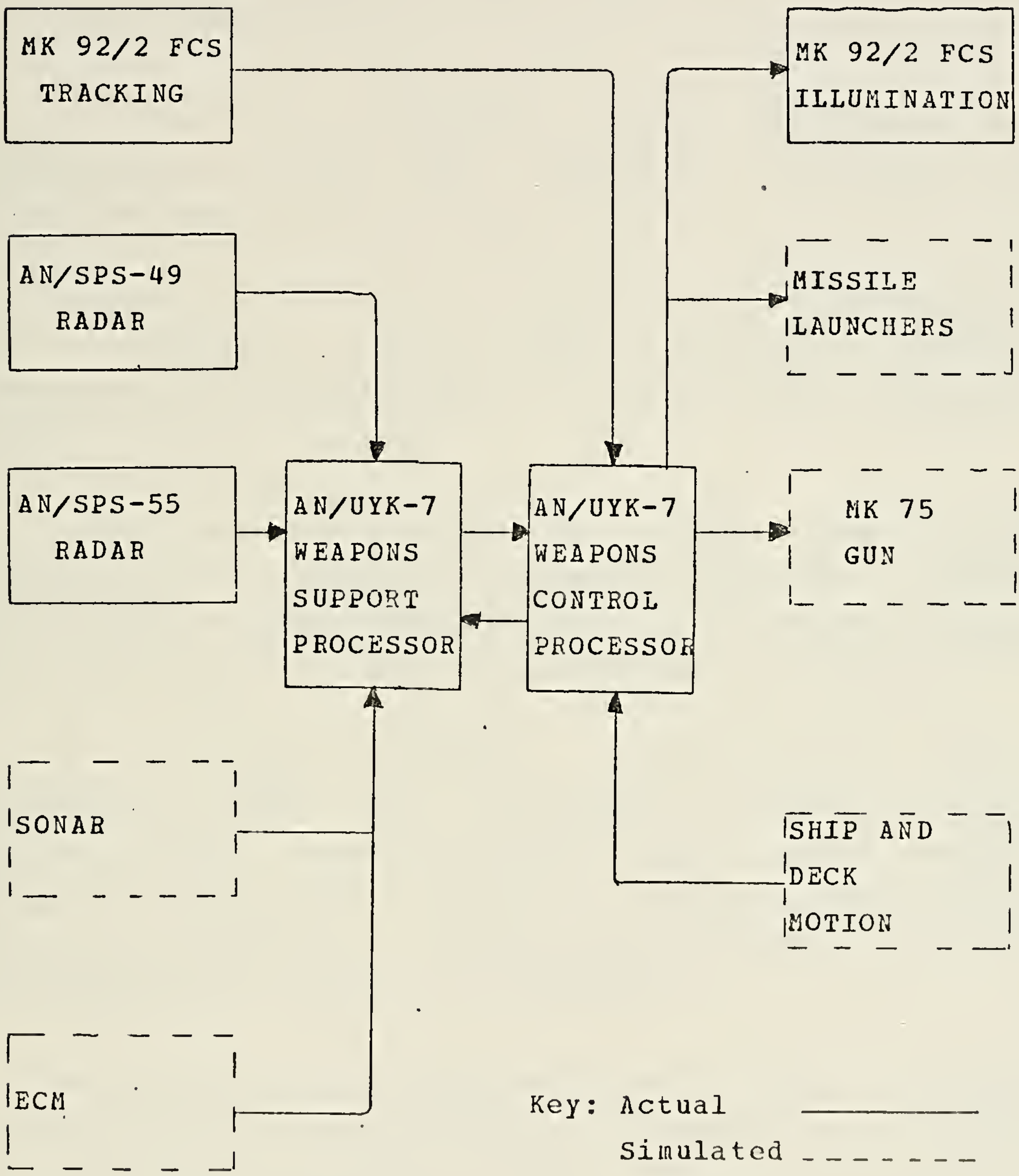



FIGURE 2

## B. A LBTS PROBLEM

The PF Development Concept Paper [Ref. 7] outlines the following critical test and evaluation questions and issues:

(1) Are the individual combat subsystems to be incorporated in the ship technically acceptable and operationally suitable and effective?

(2) Does the integrated propulsion system installed at the Propulsion System LBTS demonstrate sufficient performance and reliability to indicate that operational requirements will be met?

(3) Is the integration of the various Combat Systems through their respective interfaces adequate, in terms of data transfer characteristics such as handling capacity, rate and quality, to meet operational requirements?

(4) Do those operational characteristics of the integrated Combat and Propulsion Systems, including reliability and maintainability, which can be estimated based on IOT&E, show a reasonable probability that the ship class when afloat will be able to satisfactorily accomplish the mission for which it was designed?

One of the decision problems, then, for the PF Project Manager was what the composition of subsystems should be in the Combat and Propulsion Systems LBTS so that "adequate test and evaluation" [Ref. 4] with satisfactory results can be supplied to DSARC III, scheduled for May 1975. The installation and testing of these PF subsystems are to be accomplished to ensure that the critical test and evaluation questions outlined in the Development Concept Paper [Ref. 7]

are answered at minimum cost. Additionally, the primary objective of the LBTS after DSARC III production approval will be to verify operating, maintenance and test procedures, to provide operational training and to test system upgrading [Ref. 8].

the Project Manager was faced with a complex problem to solve. The problem contains the multiple measures of effectiveness of cost, schedule and future usefulness under consequences of varying degrees of uncertainty. It is this problem which was used in Chapters IV and V to illustrate a decision analysis approach to project management trade-off situations. Chapter III contains a description of the methodology necessary to formulate and solve the problem.

# III. DECISION ANALYSIS METHODOLOGY

Man is often confronted with situations in which the consequences of any action he takes are not certain. Events may intervene which he can not control or predict with certainty. A large number of decisions under uncertainty are made by intuition [Ref. 9]. The intuitive decision process is accomplished in the decision-maker's mind. Because of this, there is no way to verify that this type of decision is the logical consequence of the choices, information and preferences that were available to the decision-maker. For many problems, however, it is important that the decision-maker is able to show people why he arrived at a particular decision and also for them to be able to see what changes in factors surrounding that decision might have led to a different decision [Ref. 9]. Another characteristic of the intuitive decision process is the human tendency to equate the quality of the decision with the quality of the outcome it produces. For example, consider a situation where an investor decides to buy some new stock. If he loses money, the tendency is to say that the investor made a bad decision; conversely, if he makes money, then he made a good decision. A good decision is a decision which maximizes the probability of a good outcome; hence, making a good decision is no guarantee of a good outcome. The decision-maker has control of the decision. He does not have control of the outcome.

The purpose of decision analysis is to allow the decision-maker to make consistent good decisions and to formulate them in quantitative terms that can be conveyed from one person to another. Formal decision analysis is a

systematic process comprising the following steps:

(1) structuring the problem,

(2) assessing relative preferences for possible consequences,

(3) evaluating the probabilities for uncertainties and

(4) determining the best course of action from the information in the preceeding steps [Ref. 10].

This process is an iterative process. First, a broad description of the problem with rough assessments of the preferences for the consequences and probabilities for the uncertainties is analyzed. On the basis of the first analysis, alternatives are added or removed from consideration. The measurements are refined and the process is repeated until there is satisfaction with the results of the analysis [Ref. 11].

The purpose of this chapter is to acquaint those unfamiliar with decision analysis with its theory and techniques to the extent necessary to formulate and solve the PF Land Based Test Site problem introduced in Chapter II. This chapter is organized to explain the methodology of decision analysis for each step in the formal analysis. Before proceeding, it is necessary to explain certain terms and notations which are used throughout the remaining parts of this thesis.

## A. CLARIFICATION OF TERMS AND NOTATIONS

The terms "is indifferent to", "is preferred to", "lottery" and "utility function", are widely used in the following sections of this thesis. For clarity, they need to be explained. The term "is indifferent to" is to be used to mean the same as the statement "the decision-maker is indifferent to receiving either of the outcomes." The term "A is preferred to B" is to be used to mean the same as the

statement "the decision-maker prefers A over B."

The term "lottery" is defined as a gamble of some uncertain event E where the prize $X^*$ is won if the event E occurs and the prize $X_*$ is won if the event E does not occur. Let $p^*$ represent the probability that E occurs and let $1 - p^*$ represent the probability that E does not occur. Notationally, the lottery $L_E$ will be represented as $\langle X^*, p^*, X_* \rangle$.

The term "utility function" is defined as a function u which assigns a real value to every consequence a and b such that u(a) is larger than u(b) if and only if a is preferred to b [Ref. 10]. The notation u(a) is expressed as the "utility of consequence a" and is represented by a real number.

With the above terms clarified, the steps in a formal decision analysis process can be explained. The first step in this process is structuring of the problem.

## B. PROBLEM STRUCTURE

In structuring a problem in which events are uncertain, the options or alternatives are enumerated. Next, all the events that can possibly occur are specified. As a last step, the alternatives and uncertain events are arranged in chronological order.

A type of diagram known as a decision-flow diagram or "tree" is a useful tool in decision analysis. It is a chronological arrangement of the alternatives which are controlled by the decision-maker and the events determined by chance [Ref. 11]. To illustrate the construction of a decision-flow diagram, consider the following problem. A decision-maker is faced with two alternatives, I and II. Both alternatives involve a situation where the outcomes a or b are uncertain. If a occurs, then the decision-maker must decide between alternatives III and IV. Alternative III also involves an uncertain situation leading to either the outcome c or d.

The decision-flow diagram is shown in Figure 3. Observe that the branching points or forks are of two types: decision forks and chance forks. A decision fork is designated by a small square and a chance fork by a small circle. There is additional information provided in the diagram which will be discussed in the sections below.

With the alternatives and uncertain events described by a decision-flow diagram, the next step in the decision analysis process is the assessment of the relative preferences for the consequences.

## C. ESTABLISHMENT OF PREFERENCES

The establishment of preferences for the consequences provides the decision-maker with the basis for the rational choice between the alternatives. This depends upon the views and attitudes of the decision-maker. The consequences may encompass a number of factors or attributes such as cost, schedule and performance. These attributes might also be of an intangible nature such as goodwill, morale and politics.

EXAMPLE DECISION-FLOW DIAGRAM

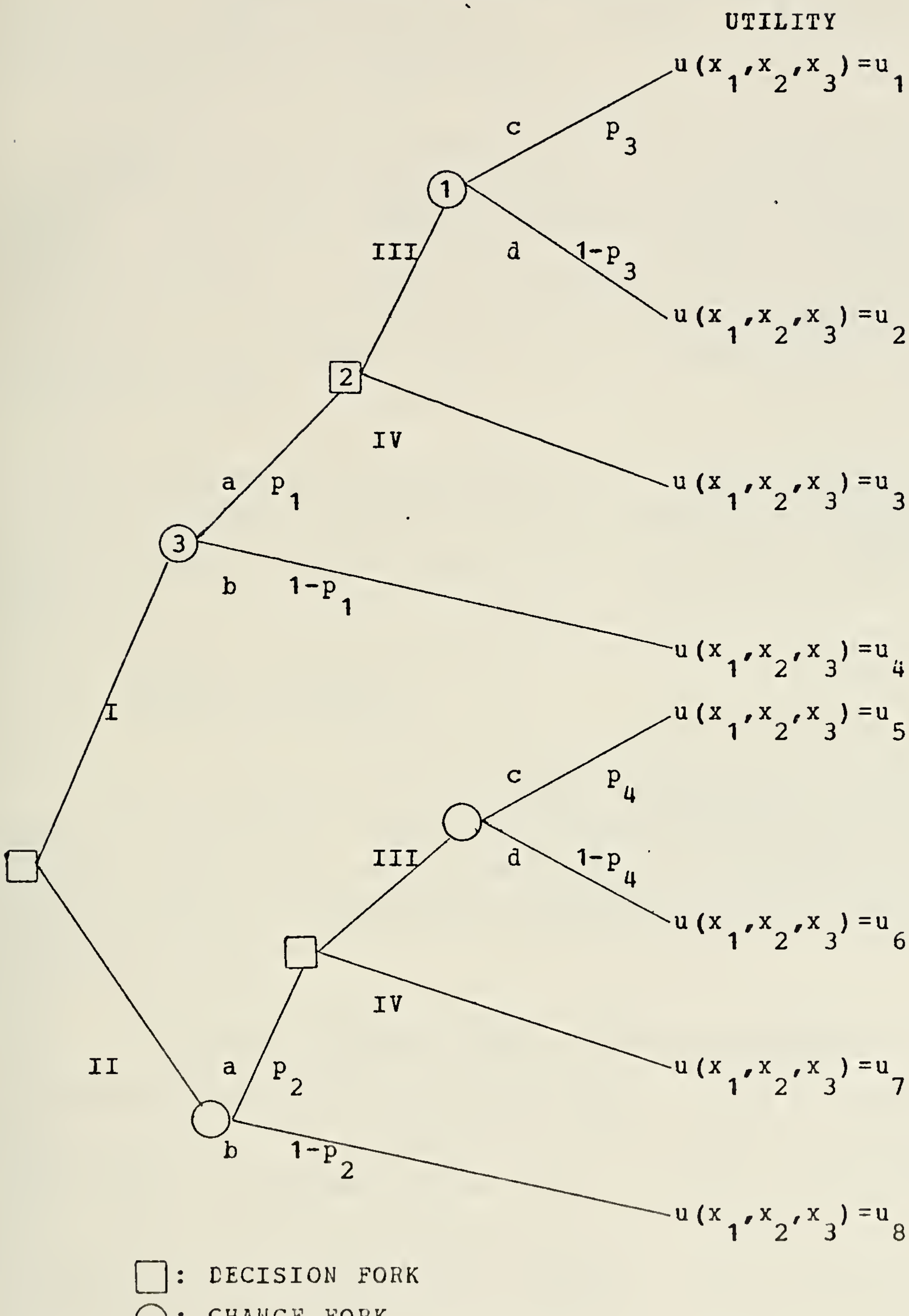



FIGURE 3

In this step in the decision analysis process, an objective function is defined to indicate a measure for the preferences for the consequences.

A general methodology for defining an objective function in decision analysis problems exists in the form of utility theory. In this thesis no attempt is made to develop the theory in detail. It will be developed only to the extent necessary to formulate and solve the PF LETS problem. The development draws heavily upon work by Giauque [Ref. 12] and Keeney [Ref. 13].

Consequences may be described by a single attribute or a multiple set of attributes. Both situations are applicable to the analysis in this thesis and are separately presented below.

1. Single Attributes

In the case of a single attribute, an objective function, hereafter called a utility function, can be defined which has the property that the maximum expected utility among the alternatives indicates the most preferred action [Ref. 12].

A utility function with a single attribute can be constructed in the following manner. Define $X^*$ and $X_*$ as the upper and lower limits over a range of possible consequences $X_i$ such that $X^* \geq X_i \geq X_*$. For every possible consequence $X_i$, define the utility $u(X_i)$ as the value $p_i$

such that the decision-maker is indifferent to receiving $X_i$ for certain and receiving the lottery $<X^*, p_i, X_*>$. The value of $p_i$ ranges from zero to one, where by convention, $u(X^*)$ equals one and $u(X_*)$ equals zero [Ref. 12].

Once a set of points $(X_i, p_i)$ have been established, a utility curve may be drawn. Figure 4 illustrates three possible utility curves. A utility curve generally has two characteristics. It is smooth and the general shape of the curve is either convex, straight or concave as illustrated respectively by curves 1, 2 and 3 of Figure 4. Any break in the curve would indicate either an inconsistency in the choices for $p_i$ in the lottery $<X^*, p_i, X_*>$ used to assess the points of the curve, or a quantum jump in preference for a small change in $X_i$. A convex curve indicates a risk averse behavior [Ref. 11]. That is, the decision-maker is more inclined to take a consequence known for sure than to take a gamble with the same expected value. A concave curve indicates that the decision-maker is risk seeking. He is more inclined to take the gamble than to take the known consequence. A straight line indicates that the decision-maker acts on the expected value of the consequence [Ref. 11]. He is neither risk averse nor risk seeking.

Once the utility curve is established for a single attribute consequence, a value from one to zero is assigned to each consequence corresponding to the point on the curve.

A higher value for a consequence indicates greater preference for that consequence than for a consequence with a lower utility value. Reference 14 contains detailed treatment of utility functions with single attributes.

EXAMPLES OF UTILITY CURVES

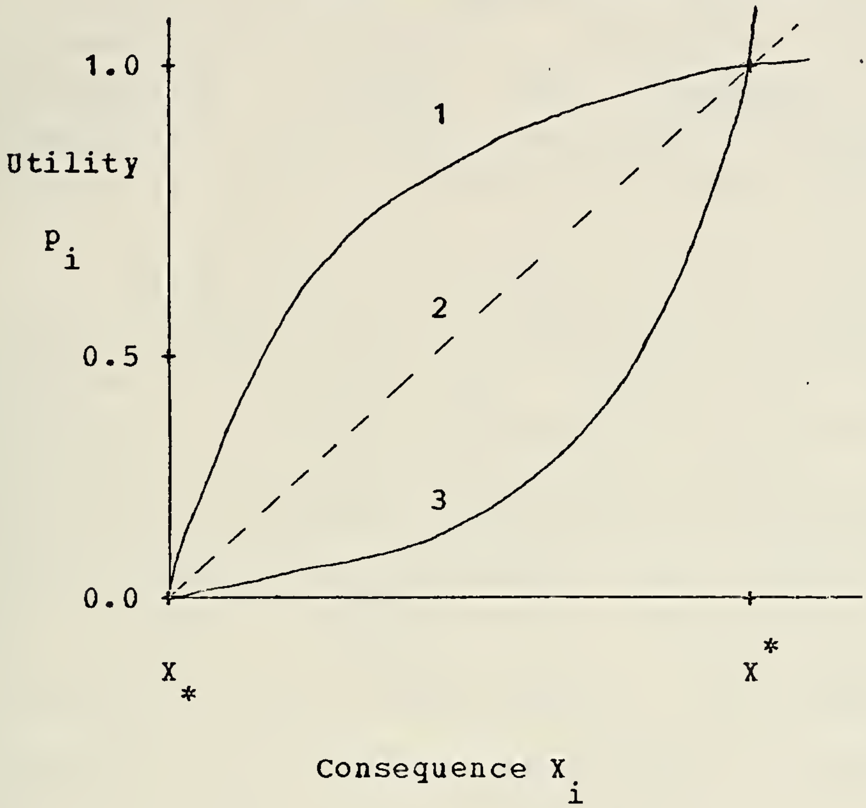



FIGURE 4

## 2. Multiple Attributes

The basic concept of the construction of a utility function with a single attribute described above can be generalized to the case where many attributes must be considered. However, the above assessment scheme is impractical. First, too many points must be assessed. Secondly, humans find it difficult to think in terms of multiple attributes. In decision problems under uncertainty, many people when faced with situations where

more than one attribute is relevant, tend to pick the one attribute judged most important to them and then make the decision on that factor alone [Ref. 10].

There are procedures for decomposing a multiple attributed utility function into combinations of unidemensional functions. Conditions required for decomposition include the properties of utility independence, pairwise preferential independence and pairwise marginality. These are described below.

Keeney [Ref. 13] shows that a multiattributed utility function can be expressed in one of two forms, additive or multiplicative, dependent on which of the properties of utility independence, pairwise preferential independence or pairwise marginality hold. If a utility function of multiple attributes can be expressed in these forms, then the task of defining the utility function is much easier. Suppose $\underline{X} = (x_1,\ldots,x_n)$ describes a consequence where $u(\underline{X})$ denotes the utility of the consequence $\underline{X}$. Utility independence is defined in the following manner. Let $x_{\bar{i}} = (x_1,\ldots,x_{i-1},x_{i+1},\ldots,x_n)$. The attribute $x_i$ is **utility independent** of $x_{\bar{i}}$ if the decision-maker's relative preference for $x_i$, with $x_{\bar{i}}$ held fixed, is the same regardless of the actual value of $x_{\bar{i}}$ chosen. Order one mutual utility independence is defined to mean that $x_i$ is utility independent of $x_{\bar{i}}$ for all i. If order one mutual utility independence holds then $u(\underline{X})$ can be expressed in the quasi-additive form

$$u(x_1,\ldots,x_n) = \sum_{i=1}^{n} u_i(x_i) + \sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}u_i(x_i)u_j(x_j) + \ldots.$$

**Pairwise preferential independence** is said to hold if the trade-offs one is willing to make between attributes taken two at a time, are not dependent on the values of the remaining attributes. Let $X_{\overline{ij}} = (x_1,\ldots,x_{i-1},x_{i+1},\ldots,x_{j-1},x_{j+1},\ldots,x_n)$, and let $x_{\overline{ij}}$ be a particular value from $X_{\overline{ij}}$. The attributes $x_i$, $x_j$ are pairwise preferentially independent of $X_{\overline{ij}}$ if one's preference order for the consequences $(x_i, x_j, x_{\overline{ij}})$ with $x_{\overline{ij}}$ held fixed, does not depend on the particular value $x_{\overline{ij}}$ [Ref. 13].

If for any pair of attributes $x_i$ and $x_j$, the lottery $<(x_i,x_j),0.5,(x_i^0,x_j^0)>$ is indifferent to the lottery $<(x_i,x_j^0),0.5,(x_i^0,x_j)>$ then **pairwise marginality** is said to hold [Ref. 12].

With the ideas of utility independence and pairwise preferential independence presented, Keeney's results can be more precisely stated [Ref. 13]. Let $\underline{X} = (x_1,\ldots,x_n)$ be as previously defined, with $n \geq 3$. If, for some $x_i$, $x_i$ and $x_j$ are pairwise preferentially independent of $(x_1,\ldots,x_{i-1},x_{i+1},\ldots,x_{j-1},x_{j+1},\ldots,x_n)$ for all $j \neq i$ and $x_i$ is utility independent of $x_{\overline{i}}$, then either

$$u(\underline{X}) = \sum_{i=1}^{n} k_i \; u_i(x_i) \qquad (1)$$

or

$$1 + K\,u(\underline{X}) = \prod_{i=1}^{n} [1 + Kk_i u_i(x_i)] \qquad (2)$$

where $u$ and $u_i$ are utility functions scaled from zero to one, the $k_i$ are scaling constants with $0 < k_i < 1$ and $K > -1$ is a non-zero scaling constant. Equation (1) is the additive form and equation (2) is the multiplicative form.

Given that the conditions of Keeney's Theorem hold, he provides a property required to show whether the function is additive (1) or multiplicative (2). He shows that if pairwise marginality holds then the function must be additive; otherwise, it is multiplicative. Table I summarizes the properties necessary for each simplification [Ref. 12].

TABLE I

UTILITY FUNCTION SIMPLIFICATION

| Simplification | Properties | | |
|---|---|---|---|
| | 1st order utility indep. | Pairwise preferential indep. | Pairwise marginality |
| Quasiadditive form | X | | |
| Multiplicative form | X | X | |
| Additive form | X | X | X |

Referring to Figure 3, there are three attributes

$x_1$, $x_2$ and $x_3$ which describe each outcome of the tree. For illustration, the following utility function might be used :

$u(x_1, x_2, x_3) = u(x_1) + u(x_2) + u(x_3) = u_i$.

This utility function, in the additive form, maps the consequences $x_1$, $x_2$ and $x_3$ into a scalar value indicated by $u_i$, where i = 1,...,8, at each branch-tip of the tree.

## D. JUDGMENTAL PROBABILITIES

The decision-flow diagram is one of the decision analysis methods used in structuring a problem. Utility functions can be used for the assignment of preferences for the consequences of the outcomes at each tip of the tree. What remains to complete the information included on the decision-flow diagram is the assignment of the judgmental probabilities at the chance forks representing the uncertain events. This is the third step in the decision analysis process.

Raiffa [Ref. 11] addresses the question of whether the decision-maker's hunches or vague impressions should be calibrated, and if so, how this should enter into the formal decision analysis process. He argues that if a decision-maker wishes to act consistently, then he ought to assign values to judgmental probabilities such that the sum of the probabilities of an event occurring and not occurring equals one. This judgmental probability assessment for an event should not depend on the outcomes. He points out that judgmental probabilities satisfy the usual rules of probability theory and can be used in the same manner as objective probabilities.

Judgmental probabilities are used as a measure of the decision-maker's beliefs concerning the uncertainty of an event occurring, provided that these beliefs are consistently applied to every uncertain event in the analysis. They are assigned to each chance fork of the tree. In Figure 3, they are represented as $p_1$, $1-p_1$, $p_2$, $1-p_2$, $p_3$, $1-p_3$, $p_4$ and $1-p_4$. With this information, the final step in any iteration of the decision analysis process is to determine the recommended course of action.

## E. RECOMMENDED COURSE OF ACTION

Determination of the recommended course of action involves a sequence of calculations called by Raiffa [Ref. 11] the "averaging out and folding back" procedure. This procedure is often referred to as the process of backwards induction in the theory of dynamic programming [Ref. 11]. The procedure starts at the tips of the tree and consists of computing the expected utility of each chance fork and the selection of the greatest utility at each decision fork. The process is repeated for each level of the tree until the starting decision fork is reached. The alternative with the greatest expected utility is selected as the recommended course of action. The selection of the maximum expected utility is an appropriate means of determining actions consistent with the decision-maker's attitudes and opinions [Ref. 12]. This point is presented and developed in such sources as Schlaifer [Ref. 16] and Pratt, Raiffa and Schlaifer [Ref. 14].

To illustrate the "averaging out and folding back" process, the information contained in Figure 3 is used. Starting at the chance fork labeled 1, the expected

utility is computed as

$$u_1 p_3 + u_2 (1-p_3) = E_1$$

Moving backwards in the tree, the next fork encountered is a decision fork, labeled $\boxed{2}$. The value of $E_1$ or $u_3$, whichever is greater, is selected. For illustration, $E_1$ is selected. Continuing backwards through the tree, a chance fork, labeled ③, is encountered. At this point, the expected utility of the chance fork is computed as

$$E_1 p_1 + u_4 (1-p_1) = E_2.$$

Alternative I has now been reached and the expected utility of this alternative is $E_2$. In similar fashion, the expected utility cf alternative II is computed. The results are compared and the alternative with the greatest expected utility is selected as the recommended course of action.

## F. SUMMARY OF CHAPTER

On most occasions, people make decisions intuitively and more or less inconsistently. There are occasions when the decision must be made in a reasoned, deliberate manner. Decision analysis methodology was introduced to provide this. In the systematic process of decisicn analysis, the decision-maker starts by structuring the anatomy of his problem in a decision-flow diagram that depicts the chronological interactions between his alternatives at any stage and the events which are controlled by uncertainty. He scales his preferences for the consequences at the tips of the decision tree in terms of utility values and scales his judgments abcut uncertain events in terms of probability assignments at the chance forks in a consistent manner.

Finally, he selects his best strategy for action by the process of "averaging out and folding back."

Most "real life" problems are complex. Trees exhibiting the structure of these problems can be so complex as to make adetailed analysis of the alternatives impractical. There is an "art" to analyzing real problems as described by Raiffa [Ref. 11]. An iterative process is used. Initially, alternatives and measurements are specified in a rough manner. Frequently, some of the decision branches will turn out to be nonoptimal and can be eliminated from the tree. If the decision branch is close to the base of the tree, a sizable portion of the tree can be eliminated. After elimination, further effort can be put into refining the description of the remainder of the tree. This iterative process is repeated until the decision can be satisfactorily made.

The necessary decision analysis methodology has now been provided. Formulation and solution of the PF Land Based Test Site problems are presented in the following two chapters.

# IV. PF LBTS PROBLEM FORMULATION

Chapter II presented the background of the PF Land Based Test Sites and developed the trade-off problem for the Program Manager as to what would be the necessary mix of PF subsystems which would be installed at the LBTS to insure adequate testing for the DSARC III review process. The Project Manager has to make sure the testing of the subsystems installed at the LBTS provide a valid estimate of the expected system operational effectiveness and suitability.

The Development Concept Paper [Ref. 7] lists in the Risk Watch List the PF subsystems which are considered to have some degree of development risk. Among these items are the Mark 92/2 fire control system, the AN/SPS-49 radar and the LM 2500 gas turbine engine. Individual Technical and Operational Evaluation are to be conducted on the subsystems listed [Ref. 5], but some seemed candidates for the Land Based Test Sites including the fire control system, radar and engine. In this chapter, the options for these three subsystems are examined more closely using the tools developed in Chapter III. This examination comprises an initial analysis proceeding in the decision analysis steps previously described. Considerable data for this analysis was provided the author by the PF Test and Evaluation Manager and the Assistant Test and Evaluation Manager during interviews with them at the PF Project Office, by correspondence and by telephone interview.

The first step in the decision analysis process is to structure the problem in terms of a decision tree. The

formulation of the problem structure is described below.

## A. PROBLEM STRUCTURE

In testing of the Mark 92/2 FCS, SPS-49 radar and LM 2500 gas turbine engine, the Project Manager is concerned with the installation and testing costs, the schedule, the usefulness of the subsystems to the PF Project at the LBTS in the future, and the uncertainty of passing DSARC III. His options for all three subsystems, in general, are:

(1) install actual or simulated equipment at the LBTS,

(2) conduct at-sea testing of each subsystem during Operational Evaluations,

(3) monitor tests at the vendor's activity or at sea or

(4) conduct no further testing.

To structure the LBTS problem, the options or alternatives are enumerated. Next, all the events that can affect the installation and testing of the subsystems are listed and arranged in chronological order. Lastly, a decision tree is constructed.

An intuitive process, in considering the options, was suggested by the PF Test and Evaluation Manager. This process is shown as a logic-flow diagram in Figure 5. To enumerate the alternatives, the options displayed in the "LBTS" boxes of the logic-flow diagram are examined.

INTUITIVE LOGIC-FLOW DIAGRAM

PF LBTS PROBLEM

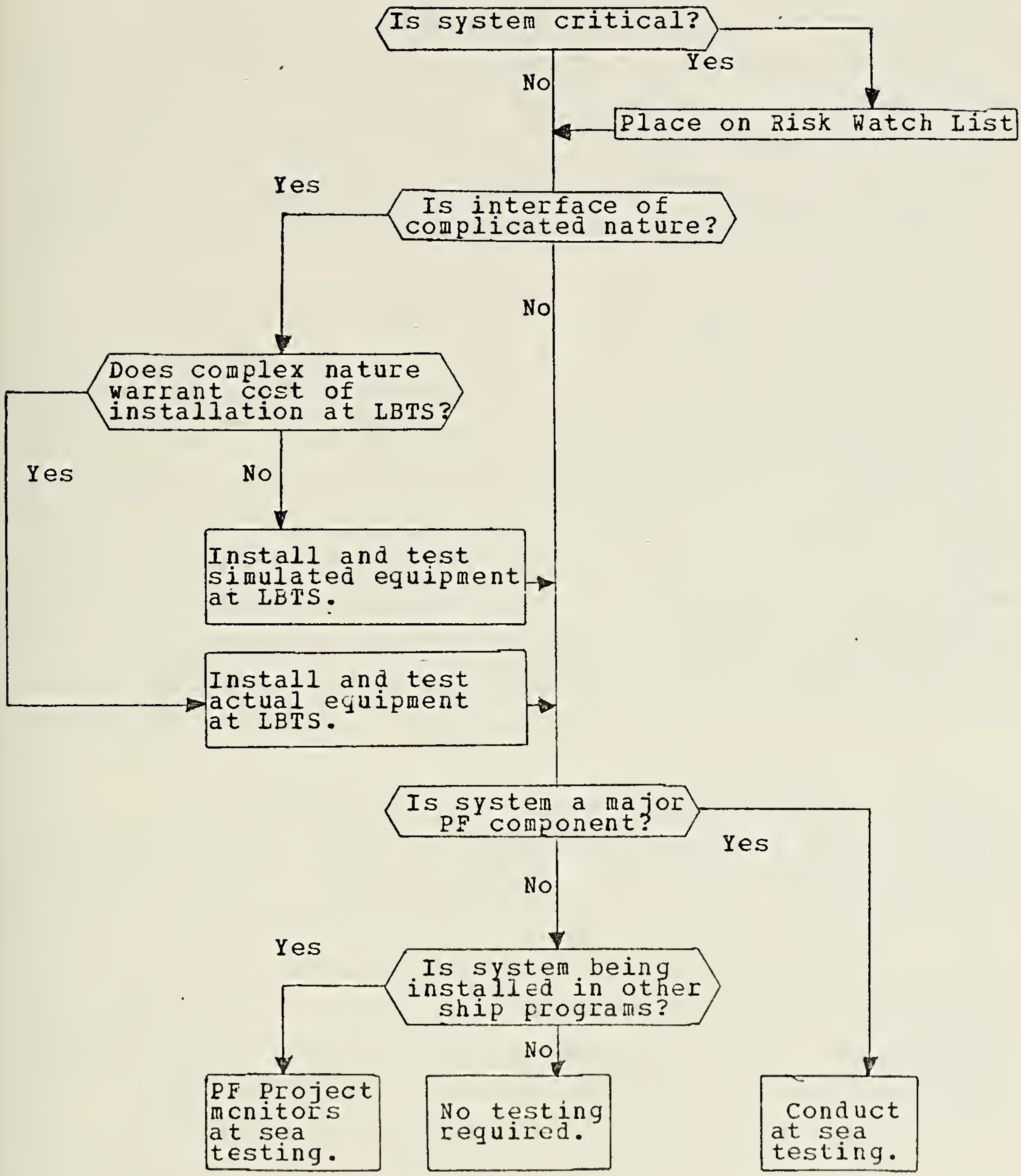



FIGURE 5

1. Alternatives

Basically, there are four alternatives considered. The first alternative is to install the actual subsystem in its entirety. The second alternative is to install a completely simulated subsystem. The third alternative is to install a partially simulated subsystem. The fourth alternative is not to install the subsystem at the LBTS.

The above alternatives apply for the installation and testing problem of the Mark 92/2 FCS. They dc not entirely apply for the cases of the SPS-49 radar or LM 2500 gas turbine. The alternative of partially simulating some components for the SPS-49 radar system was not considered. It would be just as feasible to simulate the entire radar system as to simulate some components such as the antenna and transmitter. Therefore, three alternatives were chosen for the AN/SPS-49 radar problem. They are: install the actual equipment of the radar, simulate the radar system or not install the radar at the LBTS.

The alternative of partially simulating the gas turbine engine was not considered because it does not make sense to do so. The alternative of not installing the engine at the Propulsion LBTS was also not considered since the engines must be represented if there is to be a Propulsion LBTS. The assumption is made that the Propulsion System LBTS is desirable and necessary for the develcpment of the Patrol Frigate. For the LM 2500 gas turbine engine, two alternatives are considered. They are to install the actual engine or to simulate the engine at the LBTS.

With the alternatives enumerated for the installation and testing of the three PF subsystems at the

LBTS, the events which affect them are specified and arranged in time sequence.

2. Events

The uncertainty of passing DSARC III scheduled for May 1975 is the primary concern of the PF Project Officer. The DSARC III review determines whether the PF development risks have been minimized so that the PF Acquisition Project may progress into the production phase. It is assumed that the Patrol Frigate is a necessary addition to the military posture for National Defense. If the DSARC III review does not consider the technical and project risks to be minimized, DSARC III will be rescheduled after all the deficiencies have been corrected. It will be at this point where the decision tree structure will be cut-off in the initial analysis of this thesis.

There are two events besides the DSARC III review which must be considered in structuring the decision tree. The first event is the LBTS Certification tentatively planned for January 1975. The second event is the Operational Assist which will be conducted by Commander Operational Test and Evaluation Force (COMOPTEVFOR) during the period February to May 1975 [Ref. 17].

LBTS Certification will consist of a series of tests conducted by the LBTS contractor to verify that the Combat System subsystems and Propulsion System subsystems have been successfully integrated, are operational and are ready to be used for other demonstrations at their respective LBTS. Certification will be approved by the PF Project Manager. If the LBTS fails Certification, additional time and money will be used to correct the deficiencies noted in order to pass Certification. If funds are not sufficient to correct

the deficiencies, the LBTS will have to be cancelled.

Another decision event occurs prior to Certification. If there is enough time to do Certification and Operational Assist, then Certification will commence as scheduled. If there is not enough time to do both, then the certification process will not be formally done and the Operational Assist will commence as scheduled [Ref. 17].

An Operational Assist project is assigned by the Chief of Naval Operations (CNO) in response to a favorable program initiation decision by the Secretary of Defense. For the case of the Patrol Frigate, it was assigned by Ref. 4. The major purpose of an Operational Assist is to establish confidence in the program worth and readiness for the commitment of resources for full-scale development [Ref. 18]. A decision event occurs if the Operational Assist is determined not satisfactory by the COMOPTEVFOR representative. At this point in time, it must be determined whether to correct the items which are unsatisfactory or to cancel the LBTS. Table II summarizes these events and their consequences in time sequence.

With the alternatives and the uncertain events arranged in chronological order, a decision tree is constructed to complete the structuring of the LBTS problem.

TABLE II

UNCERTAIN EVENTS OF LBTS

| EVENT | CONSEQUENCE | TIME-FRAME |
|---|---|---|
| 1. Time available for certification and Op Assist | If time available, do both; else, do Op Assist. | Fall 1974 |
| 2. Certification | Pass or fail. If passed, do Op Assist. If failed, do over or cancel LBTS. | January 1975 |
| 3. Op Assist | Pass or fail. If passed, do DSARC III. If failed, do over or cancel LBTS. | Spring 1975 |
| 4. DSARC III | Pass or fail. If passed, analysis done. If failed, do over. | May 1975 |

### 3. Decision Trees

Figure 6 depicts a typical branch of the decision tree for the alternatives of actual installation, partial installation or simulation of the subsystems at the LBTS. The first chance fork in the branch represents the uncertainty of the time available for Certification and Operational Assist. Only one alternative is selected at this point. If there is time available, then the alternative is to do both Certification and Operational Assist. If there is no time available for both tests, then

the alternative is to do Operational Assist only. The second chance fork represents the uncertainty of Certification. If it is passed, then the Operational Assist is conducted. If it is failed, then a decision is made to cancel the LBTS or do the Certification over. The third chance fork of the branch represents Operational Assist testing. If the Operational Assist is passed, then DSARC III commences as scheduled. If the Operational Assist is failed, then a decision is made to cancel the LBTS or do the Operational Assist over at a later date. The final chance fork is the DSARC III review. If it is passed, the most preferred consequence is achieved. If it is failed, then a decision is made to either cancel the PF Project or to reschedule DSARC III at a later date. As was pointed out above, the assumption is that the Patrol Frigate is essential to the National Defense posture, so that, in the analysis, the "do over" branch will be weighted more favorably than the "cancel" branch.

Figure 7 depicts the "no installation " branch of the decision tree for the Mark 92/2 FCS and SPS-49 radar. There is one chance fork representing DSARC III in which it is either passed or failed.

The structuring of the Land Based Test Site problem is completed. The next step in the decision analysis process is to evaluate the consequences of the decision tree in terms of utility numbers. This process is described below where a set of utility functions for one individual concerned with the problem is developed to illustrate the method and use of decision analysis.

INSTALL EQUIPMENT BRANCHES

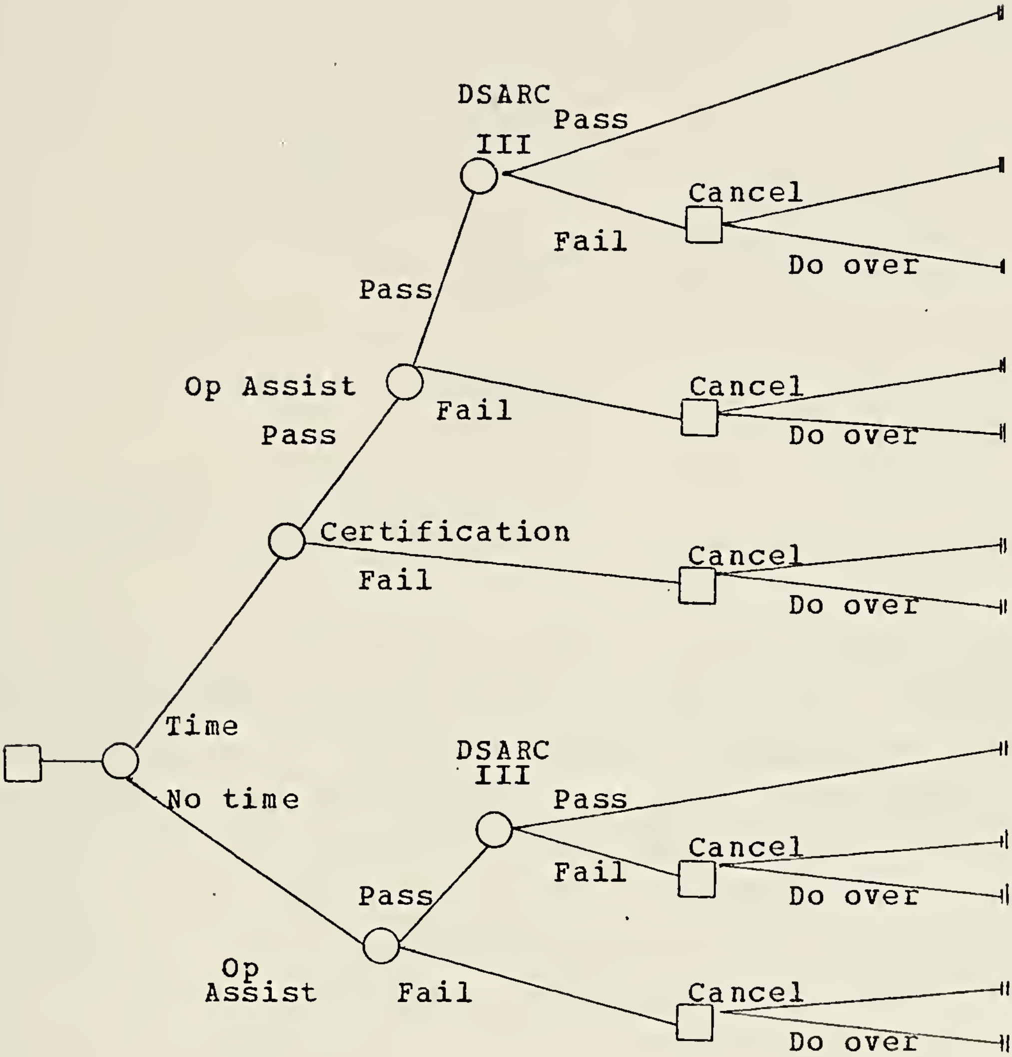



FIGURE 6

TYPICAL LBTS DECISION TREE
INSTALL NO EQUIPMENT BRANCH

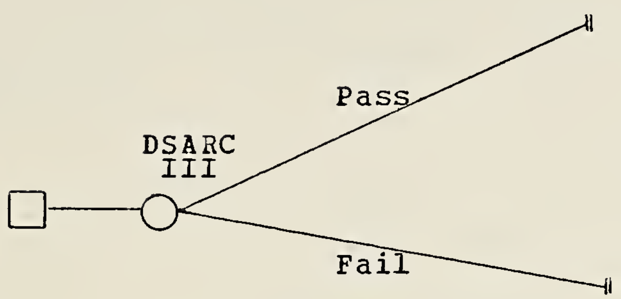



FIGURE 7

## B. ASSIGNMENT OF UTILITY NUMBERS

In order to provide a basis for the rational choice between the alternatives, utility functions are established to indicate a measure for the preferences of the consequences. The consequences for the LBTS problem are described by the attributes of cost, schedule and future usefulness. A fourth attribute, performance, was a possibility. It is assumed that all three subsystems will have to meet some previously specified performance level; therefore, a performance attribute was not considered for this initial analysis.

The attributes which describe the consequences are tangible and are measured in millions of dollars for cost, months for schedule and scalar values for usefulness. The scalar value for usefulness ranges from zero to three. The value zero is assigned for a subsystem which is not installed at the LBTS. The value one is assigned to a simulated subsystem. The value two is assigned to a

partially simulated subsystem and the value three is assigned to the installation of the actual subsystem. Table III lists the attribute ranges determined from interviews with the PF Test and Evaluation Manager and the Assistant Test and Evaluation Manager [Refs. 17,19]. The values for cost and schedule have been generalized reflecting an order of magnitude only.

TABLE III

ATTRIBUTE RANGES

| | COST (million) | USEFULNESS (scalar) | SCHEDULE (month) |
|---|---|---|---|
| 1. AN/SPS-49 | | | |
| minimum | 1.5 | 0. | 1.5 |
| maximum | 3.5 | 3 | 4.0 |
| 2. MK 92/2 FCS | | | |
| minimum | 7.5 | 0 | 1.5 |
| maximum | 18.5 | 3 | 6.0 |
| 3. LM 25C0 GT | | | |
| minimum | 3.0 | 0 | 10.0 |
| maximum | 15.0 | 3 | 16.0 |

Since a consequence for the LBTS problem is represented by multiple attributes, the utility function will be described, in some form, by a combination of the individual attribute utility functions. Once they are established, the utility function might be expressed in the additive or multiplicative forms exhibited in Chapter III dependent on the properties of the attributes. Establishment of the individual attribute utility functions is first discussed.

### 1. Individual Attribute Utility Functions

A discrete utility function consisting of four points was established for the usefulness attribute in the analysis of all three subsystems. A straight line utility function for the schedule attribute for the SPS-49 radar decision tree was derived and a family of four utility curves was established for the schedule attribute describing the consequences of the fire control and gas turbine decision trees. A straight line utility function representing the cost attribute was derived for all three subsystem decision trees. Table IV summarizes the results. The method for arriving at these utility functions is discussed in the paragraphs below.

The attribute of future usefulness consists of four integers, zero, one, two and three. The utility of the value zero is zero since it is least preferred and the utility of the value three is one since it is most preferred. To assess the utility of the values one and two, the PF Assistant Test and Evaluation Manager was asked the following questions [Ref. 17]:

"If you are indifferent between the future usefulness value one and the lottery $<3,p_1,0>$, what do you feel the probability $p_1$ of getting a future usefulness value three is?"

"If you are indifferent between the future usefulness value two and the lottery $<3,p_2,0>$, what do you feel the probability $p_2$ of getting a future usefulness value three is?"

The reply to these questions was that $p_1$ would be 0.5 and $p_2$ would be 0.85. With this information, the utility function for the attribute future usefulness was evaluated. Given four discrete values, 0, 1, 2 and 3, with $u_1(0) = 0$ and $u_1(3) = 1$, then

$$u_1(1) = 0.5\ u_1(3) + 0.5\ u_1(0) = 0.5$$

and

$$u_2(2) = 0.85\ u_1(3) + 0.15\ u_1(0) = 0.85.$$

A utility measure for the schedule attribute for the three PF subsystems will not have similar worth. As was disclosed in conversations with the PF Project Assistant Test and Evaluation Manager [Ref. 20], the schedule for the AN/SPS-49 radar is not critical. In assessing a utility function for this subsystem, he would be indifferent to gambles with respect to the schedule. He also indicated for the Mark 92/2 FCS and gas turbine engine, their schedules are very critical. If he is afforded a choice between a gamble consisting of uncertain schedules and a schedule which was known, then he would take the known schedule in every case, indicating a risk averse behavior. He added that as long as the installation and test schedule were met for DSARC III, he would evaluate the utility of any schedule less than the maximum as one.

The ranges for the maximum and minimum schedule for the radar are 1.5 and 4.0 months. Since the preferences for schedule uncertainties for the SPS-49 radar are not risk averse, a straight-line utility function can be used to express the expected value for the installation and testing

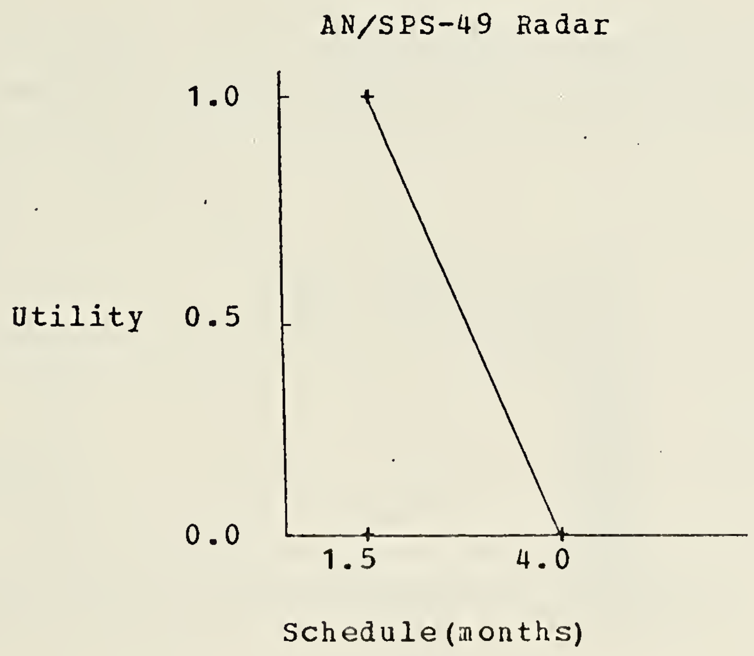
schedule. The straight line connects the point $(x_2=4.0, u_2(4.0)=0)$ with the point $(x_2=1.5, u_2(1.5)=1)$. Since the function represents the expected value of the SPS-49 schedule, the equation of the utility function cf the attribute schedule, $u_2(x_2)$, will be

$$x_2 = u_2(x_2)\ 1.5 + [1 - u_2(x_2)]\ 4.0$$
$$= 4 - 2.5\ u_2(x_2).$$

Hence,

$$u_2(x_2) = (4 - x_2) / 2.5.$$

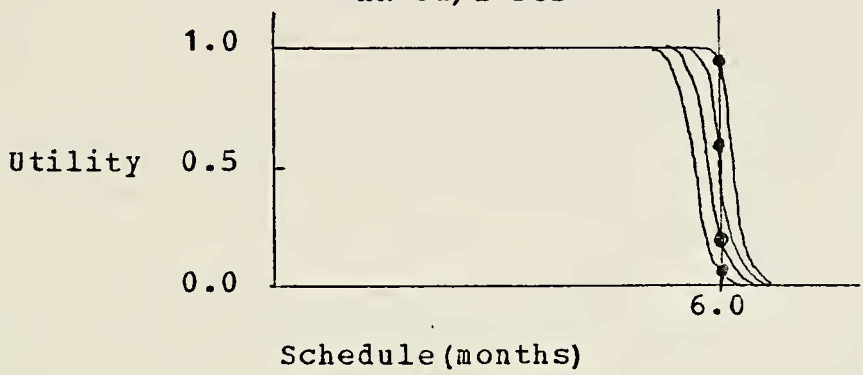
The utility function for the attribute schedule of the SPS-49 radar, is represented in the following graph:




The LM 2500 gas turbine engine schedule ranges from ten to sixteen months. The Mark 92/2 FCS schedule ranges from 1.5 to six months. Because the schedule is critical

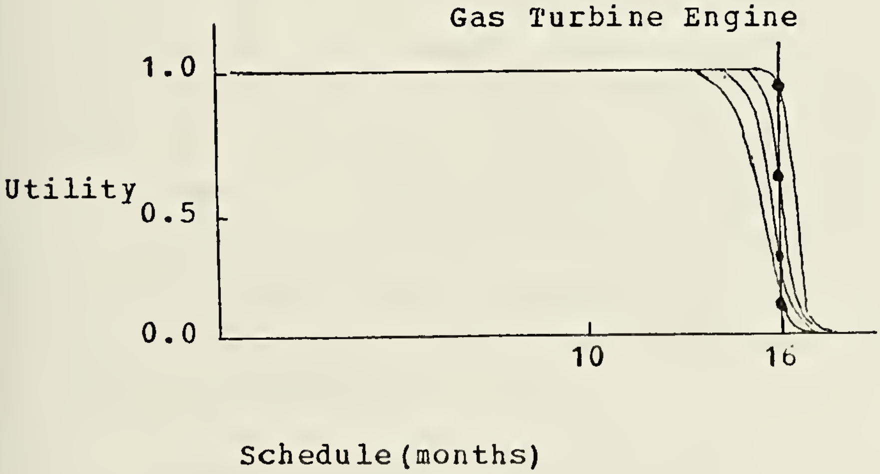
for these two subsystems, there will be risk adversion towards any gambles of uncertain schedules. A utility value of one will be assigned to any schedule that is less than the planned schedule for DSARC III. With this information, the utility function curve for the fire control system would be similar to one of the curves in the following graph. Four utility values, as indicated on the graph, will be used to determine the sensitivity of the results.

MK 92/2 FCS




The curve for the utility function of the gas turbine schedule would similarly look like one of the curves in the next graph.

Gas Turbine Engine



Values for the utility function for schedule for the engine and fire control system will be obtained from each of the four curves of the two graphs above and used in the solution of the decision trees to determine the sensitivity of the results. If there is a significant difference in the solution results between these values, then further research in the develcpment of the utility function will be required.

The evaluation of the utility function for the attribute cost was next considered. The installation and testing costs for the SPS-49 radar range from 1.5 to 3.5 million dollars. The LM 2500 gas turbine engine costs range from three to fifteen million dollars. The Mark 92/2 FCS costs range from 7.5 to 18.5 million dollars. The minimum costs represent the best costs for installation and testing, if all events are passed on schedule. The maximum costs represent the worst costs as if all events are failed and if no more funds are available to correct deficiencies.

It seemed plausible that one utility function for the three subsystems could be derived where the costs range from zero to 18.5 million dollars. From discussions with the Assistant Test and Evaluation Manager [Ref. 20], this seems to be a valid assumption. He is willing to take gambles on the basis of the expected cost values over the entire range for the three subsystems under consideration. This is justified because a vast range of assets is considered. A decision-maker, considering the vast amounts of funds available, would not be necessarily risk averse. It is realized that the cost decisions for each subsystem would be made over a much smaller range as indicated for each PF subsystem.

The utility function for costs was derived as a straight line connecting the point $(x_3=\$18.5M, u_3(\$18.5M)=0)$

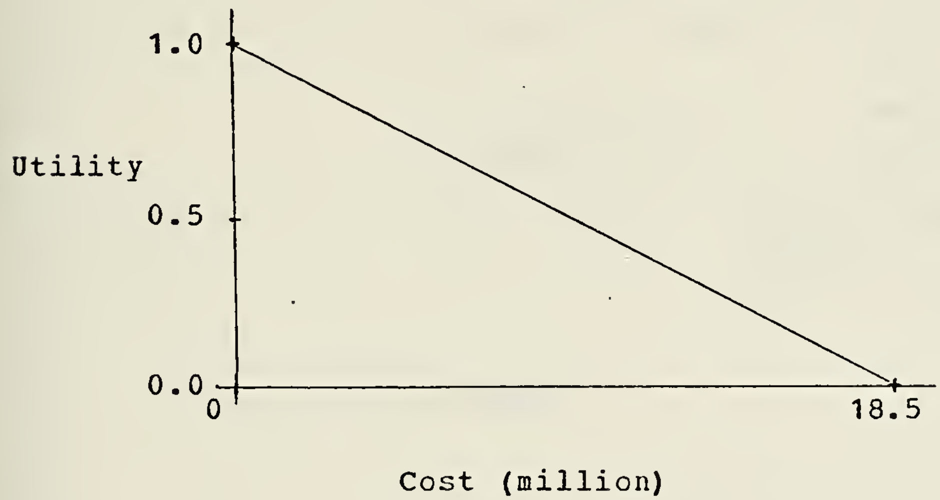
with the point $(x_3 = \$0M, u_3(\$0M) = 1)$. The equation of the utility function of cost, $u_3(x_3)$, is

$$x_3 = u_3(x_3)\ 0 + [1 - u_3(x_3)]\ 18.5$$
$$= 18.5 - 18.5\ u_3(x_3).$$

Hence,

$$u_3(x_3) = (18.5 - x_3)\ /\ 18.5$$

The utility function for the cost attribute is represented in the following graph.




With the individual attribute utility functions specified, the utility functions for the fire control, radar and gas turbine engine consequences can be represented as a combination of the three individual utility functions. This utility function may be expressed in the multiplicative or additive form dependent upon which of the attribute properties of utility independence, pairwise preferential independence or pairwise marginality hold. The next section is devoted to the verification of which of these attribute

properties hold.

TABLE IV

INDIVIDUAL UTILITY FUNCTIONS

| Attribute | Applicable to | Utility Function |
|---|---|---|
| 1. Future usefulness: | All | $u_1(0) = 0.0$<br>$u_1(1) = 0.5$<br>$u_1(2) = 0.85$<br>$u_1(3) = 1.0$ |
| 2. Schedule: | SPS-49 radar | $u_2(x_2) = (4-x_2)/2.5$ |
| | MK 92/2 FCS | Family of curves |
| | Gas Turbine | Family of curves |
| 3. Cost: | All | $u_3(x_3) = (18.5-x_3)/18.5$ |

2. Attribute Properties

If the attribute properties of order one utility independence and pairwise preferential independence hold for the attributes cost, schedule and usefulness, then the utility function can be expressed in the multiplicative form. Further, if the property of pairwise marginality also holds, then the utility function can be expressed in the additive form. These forms are shown in Chapter III.

Verification of utility independence for the attributes cost, schedule and future usefulness of the Mark 92/2 FCS problem is first considered. To verify utility

independence, consider the attribute cost of the Mark 92/2 FCS installation at the Combat System LBTS. The minimum and maximum costs were determined to be 7.5 million dollars and 18.5 million dollars. The following question is asked [Ref. 15].

"Suppose the values for future usefulness and schedule for the fire control system are specified at some given quantity, say, three and 1.5 months. Now, consider the gamble 7.5 million dollars with a probability of p and 18.5 million dollars with a probability of 1-p. Determine a dollar amount X such that if you had to choose either the gamble or the X million dollars for sure, you would be indifferent. Now, suppose I give you a different set of values for the other attributes, say, two and fifteen months, and ask you to assess X again. Does the value of X million dollars change?"

If the value of X million dollars does not change no matter what values are given for the usefulness and schedule attributes, and if this is true for all gambles on the cost attribute, then the cost attribute is utility independent of the other attributes. Utility independence of the usefulness and schedule attributes can similarly be verified [Ref. 15]. If all of the attributes are utility independent of the other attributes, then order one utility independence is established.

To verify pairwise preferential independence, consider the attributes of cost and future usefulness for the gas turbine problem. The following dialogue is held [Ref. 15].

"Consider the consequence I, involving a four million dollar installation and testing cost for the gas

turbine engine, no future usefulness and an eleven month schedule. Now, determine a dollar figure X such that consequence II defined as; X million dollars, a maximum future usefulness value of three and an eleven month schedule, is exactly as attractive as consequence I. now, let's change the value of the schedule attribute. Does the value of X million dollars change?"

If the value of X million dollars does not change for all values of the schedule attribute, and if this is true for all trade-offs between cost and usefulness, then these two attributes are pairwise preferentially independent of the schedule attribute. Pairwise preferential independence between the other pairs of attributes is determined in a similar manner [Ref. 15].

To verify pairwise marginality, a convenient test is the pairwise marginality test [Ref. 15]. As an illustration, the attributes of cost and schedule for the SPS-49 radar consequences are considered. Let lottery $L_1$ yield 3.5 million dollars and a schedule of 1.5 months with a probability of 0.5 and 3.5 million dollars and a schedule of four months with a probability of 0.5. Let lottery $L_2$ yield 3.5 million dollars and a schedule of four months with a probability of 0.5 and 1.5 million dollars and a schedule of 1.5 months with a probability of 0.5. If the decision-maker is indifferent between $L_1$ and $L_2$, then pairwise marginality holds between cost and schedule. Similarly, the pairwise marginality tests are made between all pairs of the attributes.

With the information gathered from interviews at the

Patrol Frigate Project Office, it was not unreasonable for the authcr tc verify the properties of utility independence, pairwise preferential independence and pairwise marginality. It was determined that the properties of order one utility independence and pairwise preferential independence hold for the attributes. Pairwise marginality does not hold. This result was the same for the three subsystems under analysis. By Keeney's Theorem [Ref. 13], the utility functions fcr all three subsystem problems can be represented in the multiplicative form

$$1 + K\,u(x_1, x_2, x_3) = \prod_{i=1}^{3} [1 + Kk_i u_i(x_i)]$$

where $x_1, x_2, x_3$ represents the attributes of future usefulness, schedule and cost respectively. The utility function of a single attribute $x_i$ is represented by $u_i(x_i)$.

In the assignment of utility numbers to consequences, the individual attribute utility functions have been determined and the utility function, which is a combination of the individual utility functions, can be expressed in the multiplicative form. What remains is to determine the scaling constants K, $k_1$, $k_2$ and $k_3$ so that the multiplicative utility function can be expressed in numerical terms. This determination is made in the section below.

### 3. Assessment of Utility Function Parameters

A procedure for evaluating the scaling constants, when the utility function is in the multiplicative form, is found in Ref. 13 and Ref. 15. The basic idea is to define four linearly independent equations, since there are four

unknowns, K, $k_1$, $k_2$ and $k_3$ to be evaluated [Ref. 15]. The following scheme is a convenient method for obtaining the linearly independent equations.

Consider the outcomes described by three attributes $x_i$. As a first step, the decision-maker is asked to rank the attributes in order of preference. For illustration, he ranks the attributes $x_i$ such that $x_1 > x_2 > x_3$. The utility values $m_i$ will next be determined from five outcomes. Let outcome $\underline{X}_1$ represent the best possible set of attributes $(a^*,b^*,c^*)$. Let outcome $\underline{X}_5$ represent the worst possible set of attributes $(a_*,b_*,c_*)$. Then $u(a^*,b^*,c^*) = 1$ and $u(a_*,b_*,c_*) = 0$. Let outcome $\underline{X}_2$ represent the set of attributes where the worst value for the least preferred attribute, $c_*$, replaces $c^*$ in the attribute set of outcome $\underline{X}_1$ such that $\underline{X}_2 = (a^*,b^*,c_*)$. Similarly, let outcome $\underline{X}_3$ represent the set of attributes where the worst value for the next least preferred attribute, $b_*$, replaces $b^*$, such that $\underline{X}_3 = (a^*,b_*,c^*)$. Using the same conventions, let outcome $\underline{X}_4 = (a_*,b^*,c^*)$.

To assess the utilities of the outcomes $\underline{X}_2$, $\underline{X}_3$ and $\underline{X}_4$, the decision-maker is asked to determine the probabilities of the gambles in the following situations where he is indifferent between:

(a) $\underline{X}_2$ for sure and the gamble $<\underline{X}_1, p_2, \underline{X}_5>$,

(b) $\underline{X}_3$ for sure and the gamble $<\underline{X}_1, p_3, \underline{X}_5>$ and

(c) $\underline{X}_4$ for sure and the gamble $<\underline{X}_1, p_4, \underline{X}_5>$.

Once the probabilities $p_2$, $p_3$ and $p_4$ are assessed, then

$$u(\underline{X}_2) = p_2 u(\underline{X}_1) + (1-p_2)\ u(\underline{X}_5),$$
$$u(\underline{X}_3) = p_3 u(\underline{X}_1) + (1-p_3)\ u(\underline{X}_5) \text{ and}$$
$$u(\underline{X}_4) = p_4 u(\underline{X}_1) + (1-p_4)\ u(\underline{X}_5).$$

Since $u(\underline{X}_1) = 1$ and $u(\underline{X}_5) = 0$, it follows that

$$u(\underline{X}_2) = p_2 = m_2,$$
$$u(\underline{X}_3) = p_3 = m_3 \text{ and}$$
$$u(\underline{X}_4) = p_4 = m_4.$$

The utility values $m_1$, $m_2$ and $m_3$ can be verified for consistency by asking the decision-maker to assess other gambles consisting of various combinations of the five outcomes. If the decision-maker has been consistent, then the utility values derived should be similar to the

previously derived utility values $m_1$, $m_2$ and $m_3$. If they are not similar values, the decision-maker is asked to re-assess all gambles until some consistency is achieved. Table V illustrates the above steps.

TABLE V

ILLUSTRATION OF SCALING CONSTANT EVALUATION

| OUTCOME | ATTRIBUTES $x_1$ $x_2$ $x_3$ | UTILITY OF OUTCOME |
|---|---|---|
| $\underline{X}_1$ | $a^*$ $b^*$ $c^*$ | $m_0 = 1$ |
| $\underline{X}_2$ | $a^*$ $b^*$ $c_*$ | $m_1$ |
| $\underline{X}_3$ | $a^*$ $b_*$ $c^*$ | $m_2$ |
| $\underline{X}_4$ | $a_*$ $b^*$ $c^*$ | $m_3$ |
| $\underline{X}_5$ | $a_*$ $b_*$ $c_*$ | $m_4 = 0$ |

Once the utility value $m_j$ for each of the five outcomes are defined, the scaling constant K can be determined from four linearly independent equations. Keeney [Ref. 13] shows the following relationship holds for the multiplicative form:

$$1 + K = \prod_{i=1}^{3} (1 + Kk_i) \qquad (3)$$

and, generally [Ref. 13];

$$1 + m_j K = \prod_{i=1}^{3} (1 + Kk_i) \,/\, (1 + Kk_j). \tag{4}$$

Equation (3) and equation (4) for j = 1,...,3 are used as the four linearly independent equations. From (3) and (4),

$$\begin{aligned} 1 + K &= \prod_{i=1}^{3} (1 + Kk_i) \\ &= (1 + m_j K)\ (1 + Kk_j). \end{aligned} \tag{5}$$

$$\begin{aligned} (1 + K)^3 &= \prod_{j=1}^{3} (1 + m_j K)\ (1 + Kk_j) \\ &= \prod_{j=1}^{3} (1 + m_j K) \prod_{j=1}^{3} (1 + Kk_j). \end{aligned}$$

Then from (3),

$$(1 + k)^3 = \prod_{j=1}^{3} (1 + m_j K)\ (1 + K)$$

and

$$(1 + K)^2 = \prod_{j=1}^{3} (1 + m_j K). \tag{6}$$

Equation (6) is a cubic equation in the form,

$$K\ (aK^2 + bK + c) = 0.$$

Thus, one of the values of the cubic equaticn is zero. The other twc values are:

$$[-b \pm (b^2 - 4ac)^{1/2}] \,/\, 2a.$$

Keeney [Ref. 13] proves that the range for the values of K, will be $K > -1$ where $K \neq 0$. Therefore, that value of K which is non-zero and greater than -1 is chosen. Giauque [Ref. 12] proves that there is always one and only one such value.

Once the constant K is known, the remaining scaling constants $k_1$, $k_2$ and $k_3$ are derived from equation (5),

$$1 + K = (1 + m_j K)\ (1 + K k_j);$$

Hence,

$$k_j = (1 - m_j) / (1 + m_j K). \qquad (7)$$

Appendices A, B and C outline the steps and computations made to determine the scaling constants for the fire control system, the SPS-49 radar and the gas turbine engine problem utility functions. The scaling constants are listed in Table VI.

TABLE VI

SCALING CONSTANTS

| Scaling Constants | FCS | Radar | Gas Turbine |
|---|---|---|---|
| $K$ | 0.07 | -0.52 | 1.37 |
| $k_1$ | 0.21 | 0.19 | 0.07 |
| $k_2$ | 0.42 | 0.34 | 0.26 |
| $k_3$ | 0.64 | 0.68 | 0.44 |

The utility functions, using the scaling constants from Table VI, are:

(a) for the Mark 92/2 FCS problem;

$$1+0.07u(\underline{X}) = [1+0.01u_1(x_1)][1+0.03u_2(x_2)][1+0.05u_3(x_3)],$$

(b) for the AN/SPS-49 radar problem;

$$1-0.52u(\underline{X})=[1-0.1u_1(x_1)][1-0.18u_2(x_2)][1-0.36u_3(x_3)],$$

and

(c) for the LM 2500 gas turbine engine problem;

$$1+1.37u(\underline{X})=[1+0.1u_1(x_1)][1+0.35u_2(x_2)][1+0.6u_3(x_3)].$$

The utility of $x_1$, $u_1(x_1)$, represents the utility of the attribute future usefulness, $u_2(x_2)$ represents the utility of the attribute schedule and $u_3(x_3)$ represents the utility of the attribute cost.

The second step in the decision analysis process has been completed. Utility functions in the multiplicative form have been derived so that utility numbers can be expressed for each of the consequences indicating the decision-maker's preferences for these consequences. To complete formulation of the LBTS problem, judgmental probabilities are assessed for the uncertain events of time to accomplish tests, Certification, Operational Assist and DSARC III.

## C. ASSESSMENT OF JUDGMENTAL PROBABILITIES

By informal correspondence, the PF Assistant Test and Evaluation Manager was asked to assess the probabilities for the uncertain events for the installation and testing of the three subsystems under analysis. Table VII summarizes the results of his reply. The probabilities indicated in this table are assigned to the appropriate chance forks of the three decision trees.

TABLE VII

JUDGMENTAL PROBABILITIES FOR LBTS PROBLEM

A. <u>If actual equipment installed</u> :

| Probability of: | MK 92 FCS | SPS-49 | LM 2500 ENG |
|---|---|---|---|
| 1. sufficient time for Certification | 0.4 | 0.8 | 0.01 |
| 3. passing Op Assist given passed Certification | 0.7 | 0.7 | 0.8 |
| 4. passing Op Assist given no Certification done | 0.2 | 0.6 | 0.3 |
| 5. passing DSARC III if passed Certification and Op Assist | 0.8 | 0.7 | 0.8 |
| 6. passing DSARC III if passed Op Assist but no Certification done | 0.1 | 0.5 | 0.2 |

B. <u>If part of system simulated</u>:

| Probability of: | MK 92 FCS |
|---|---|
| 1. sufficient time for Certification | 0.4 |
| 2. passing Certification if time available | 0.5 |
| 3. passing Op Assist given passed Certification | 0.4 |
| 4. passing Op Assist given no Certification done | 0.2 |
| 5. passing DSARC III if passed Certification and Op Assist | 0.6 |
| 6. passing DSARC III if passed Op Assist but no Certification done | 0.1 |

C. <u>If all of system simulated</u>:

| Probability of: | MK 92 FCS | SPS-49 | LM 2500 ENG |
|---|---|---|---|
| 1. sufficient time for Certification | 0.2 | 0.7 | 0.4 |
| 2. passing Certification if time available | 0.3 | 0.7 | 0.35 |
| 3. passing Op Assist given passed Certification | 0.2 | 0.7 | 0.4 |
| 4. passing Op Assist given no Certification done | 0.1 | 0.6 | 0.2 |
| 5. passing DSARC III if passed Certification and Op Assist | 0.1 | 0.5 | 0.5 |
| 6. passing DSARC III if passed Op Assist but no Certification done | 0.05 | 0.4 | 0.5 |

D. <u>If system were not installed at LBTS</u>:

| Probability of: | MK 92 FCS | SPS-49 |
|---|---|---|
| 1. passing DSARC III | 0.2 | 0.6 |

D. SUMMARY OF CHAPTER

The systematic process of decision analysis was used to formulate the problem of deciding whether to install actual subsystems, partially simulate them or simulate the entire subsystem at the Patrol Frigate LBTS. The alternative of not installing the subsystem at the LBTS was also considered. Three subsystems were chosen from the Risk Watch List for the analysis. They are the Mark 92 mod 2 fire control system, the AN/SPS-49 radar and the LM 2500 gas turbine engine. In section A. of this chapter, the structure of the problem was formulated in terms of a decision tree. Figure 6 illustrates a typical branch of the decision tree for the installation of actual equipment, partially simulated equipment or simulated equipment.

Figure 7 illustrates the "no installation" alternative branch of the decision tree. Section B. contained a discussion of the second step in the decision analysis process, assessment of the decision-maker's preferences for the consequences. They are expressed in terms of utility numbers. A utility function which assigns the utility numbers to the consequences was formulated in the multiplicative form. The equations derived are shown in this section. Section C. comprised the third step in the decision analysis process, assessment of the judgmental probabilities for each chance fork of the decision tree. Table VII lists these probabilities.

Chapter V contains a discussion of the final step in the decision analysis process, determination of the best courses of action using the information formulated in this chapter. The word "final" implies that the process is completed when the best course of action is determined. As was pointed out, the decision analysis process is iterative. This thesis represents the initial analysis of a complicated problem. In the conclusion, Chapter VI, some suggestions for further research to refine the analysis of this thesis are made.

## V. PF LBTS PROBLEM SOLUTION RESULTS

All of the information required to solve the PF LBTS problem, including a discussion of the alternatives and consequences for each subsystem, and cost, schedule and usefulness considerations have been provided in the preceeding chapter. The functions which transform the three attributes into a scalar measure of utility for the outcomes were derived, and judgmental probabilities were assessed for each uncertain event of the decision tree. All that remains is to structure the decision tree, assign the appropriate utility to each end point, insert the judgmental probabilities at the chance forks and determine the expected utility values for each alternative of the tree.

in this chapter, the solution results for the AN/SPS-49 radar, the Mark 92/2 FCS and the LM 2500 gas turbine problems will be discussed separately. In each case, the decision tree is provided before the results are discussed. The decision trees presented are analyzed by computing the expected utility of each chance fork and the selection of the greatest utility at each decision fork. The process is repeated for each level of the tree until the starting decision fork is reached. The alternative with the greatest expected utility is selected as the best course of action. A computer program written in the BASIC language, was used to perform the calculations.

### A. SPS-49 RADAR

The decision tree for the AN/SPS-49 radar problem is

exhibited in Figure 8. The alternatives which were considered are: installation of the actual equipment, installation of simulated equipment or no installation. The assessed judgmental probabilities are indicated near each "Pass" and "Fail" of the chance forks. Table VIII lists the outcomes for each of the twenty-six consequences and provides the utility for each consequence. The utility functions derived for the AN/SPS-49 radar problem are shown in section B.3. of the previous chapter.

The sclution results are:

(1) the expected utility of the alternative, installation of the actual equipment, is 0.76,

(2) the expected utility of the alternative, simulation of the equipment, is 0.72 and

(3) the expected utility of the alternative, no installation, is 0.81.

These results indicate that the recommended course of action is not to install the SPS-49 radar at the Combat System LBTS.

DECISION TREE SPS-49 RADAR

ACTUAL EQUIPMENT AND NO EQUIPMENT BRANCHES

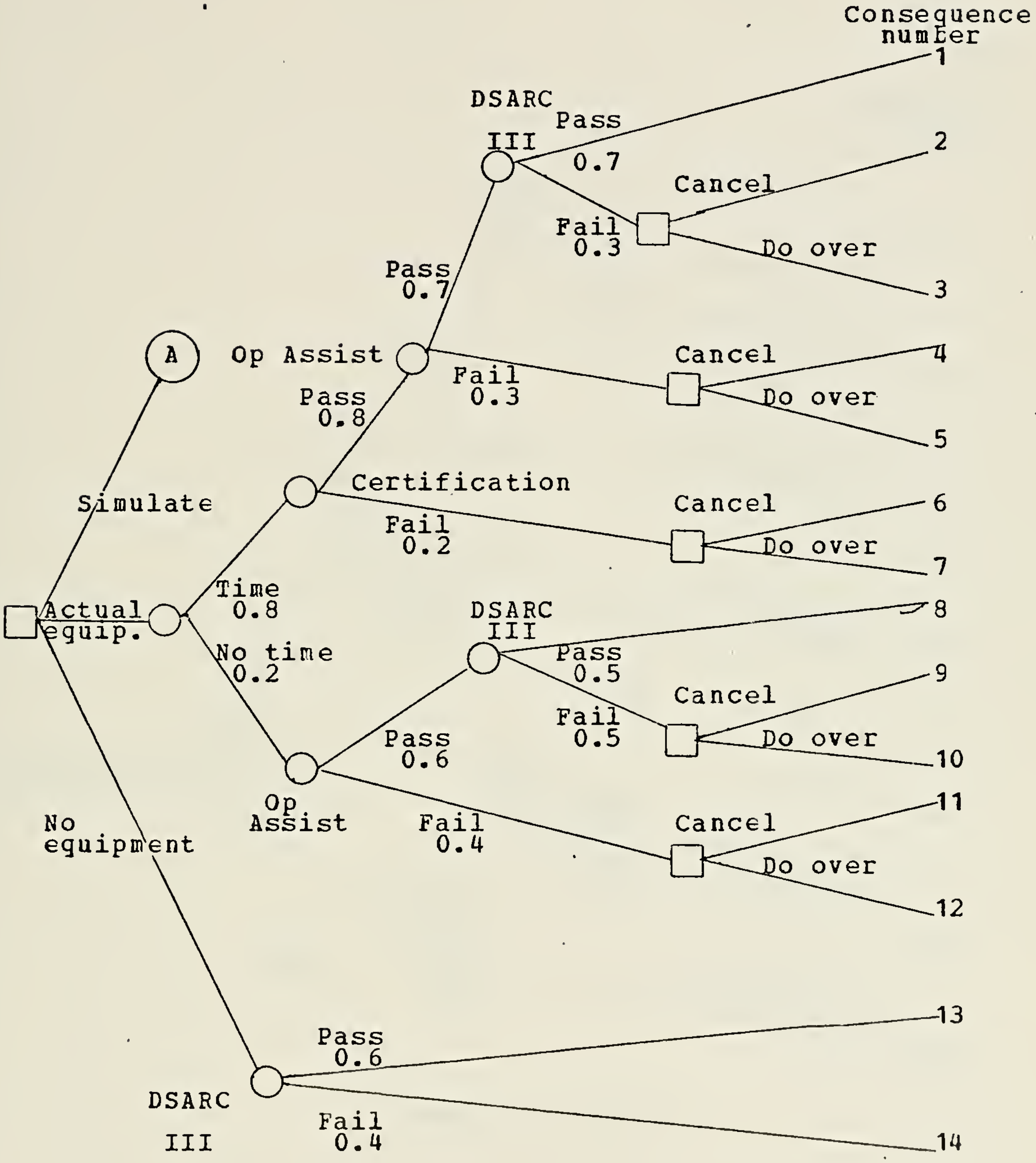



FIGURE 8

DECISION TREE SPS-49 RADAR

SIMULATE BRANCH

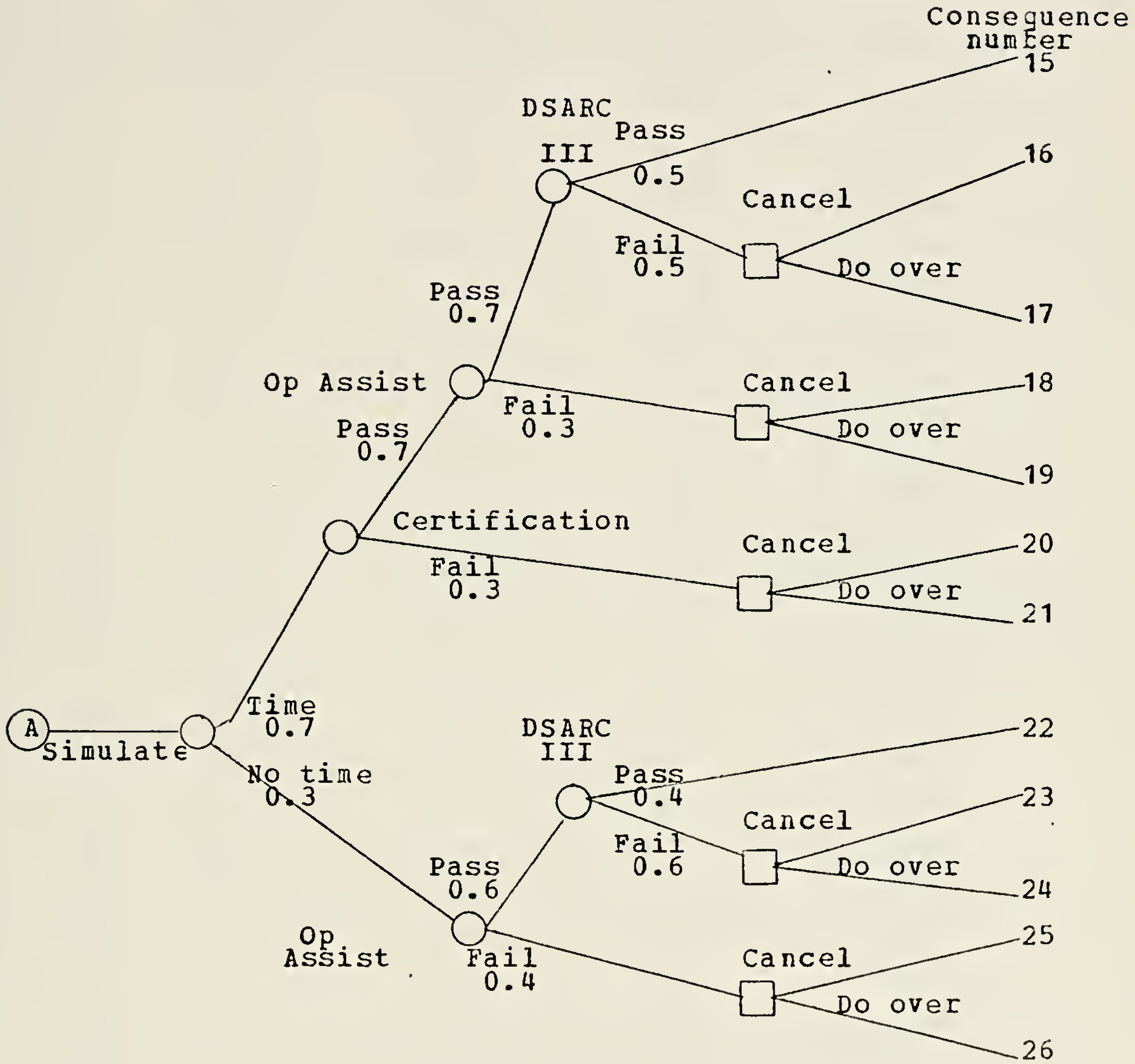



FIGURE 8 (continued)

TABLE VIII

OUTCOMES AND RESULTS OF SPS-49 DECISION TREE

| CONSEQUENCE Number | OUTCOMES Usefulness (scalar) | Schedule (month) | Cost (million) | UTILITY |
|---|---|---|---|---|
| 1 | 3 | 1.5 | 2.5 | 0.93 |
| 2 | 0 | 4 | 3.5 | 0.55 |
| 3 | 3 | 4 | 3.5 | 0.68 |
| 4 | 0 | 4 | 3.5 | 0.55 |
| 5 | 3 | 4 | 3.5 | 0.68 |
| 6 | 0 | 4 | 3.5 | 0.55 |
| 7 | 3 | 4 | 3.5 | 0.68 |
| 8 | 3 | 4 | 2.5 | 0.72 |
| 9 | 0 | 4 | 3.5 | 0.55 |
| 10 | 3 | 4 | 3.5 | 0.68 |
| 11 | 0 | 4 | 3.5 | 0.55 |
| 12 | 3 | 4 | 3.5 | 0.68 |
| 13 | 0 | 0 | 0 | 0.90 |
| 14 | 3 | 4 | 3.5 | 0.68 |
| 15 | 1 | 1.5 | 1 | 0.92 |
| 16 | 0 | 4 | 2 | 0.60 |
| 17 | 1 | 4 | 2 | 0.67 |
| 18 | 0 | 4 | 2 | 0.60 |
| 19 | 1 | 4 | 2 | 0.67 |
| 20 | 0 | 4 | 2 | 0.60 |
| 21 | 1 | 4 | 2 | 0.67 |
| 22 | 1 | 4 | 1 | 0.70 |
| 23 | 0 | 4 | 2 | 0.60 |
| 24 | 1 | 4 | 2 | 0.67 |
| 25 | 0 | 4 | 2 | 0.60 |
| 26 | 1 | 4 | 2 | 0.67 |

SOLUTION RESULTS

| ALTERNATIVE | EXPECTED UTILITY |
|---|---|
| 1. Actual | 0.76 |
| 2. Simulated | 0.72 |
| 3. None | 0.81 |

## B. MARK 92 MOD 2 FCS

The decision tree for the Mark 92/2 FCS problem is exhibited in Figure 9. The alternatives which were considered are: installation of the actual equipment, partial simulation of the equipment, complete simulation of the equipment and no installation. The assessed probabilities are indicated near each "Pass" and "Fail" of the chance forks of the tree. Table IX lists the outcomes for each of the consequences and provides a range of utilities for each consequence. Recall that a family of utility curves was established for the schedule attribute. Hence, for the fire control system problem, four different sets of points for the schedule attribute were used to check the sensitivity of the shape of these curves on the solution. The utility functions derived for the fire control system installation problem are shown in section B.3. of the previous chapter.

The solution results are:

(1) the expected utilities for the alternative, installation of the actual equipment, range from 0.38 to 0.63,

(2) the expected utilities for the alternative, partial simulation of the equipment, range from 0.50 to 0.78,

(3) the expected utilities for the alternative, simulation of the equipment, range from 0.40 to 0.70 and

(4) the expected utilities for the alternative, no installation, range from 0.43 to 0.67.

These results indicate that the recommended course of action

is to partially simulate the fire control system to be installed at the Combat System LBTS. They are consistent over the entire range of the utilities. The different shapes of the schedule attribute utility curve do not affect the solution results.

## C. LM 2500 GAS TURBINE ENGINE

The decision tree for the gas turbine engine problem is shown in Figure 10. Two alternatives were considered. They are: installation of the engines or simulation of the engines. The assessed judgmental probabilities are indicated near each "Pass" and "Fail" of the chance forks of the tree. The outcomes for each of the twenty-four consequences and a range of utilities for the outcomes are provided in Table X. As with the fire control system problem, a family of curves was established to represent the utility curve of the schedule attribute. The range of utilities represent four different sets of points used to check the sensitivity of the shape of these curves on the solution results.

The sclution results are:

(1) the expected utilities of installing the gas turbine engines range from 0.19 to 0.35 and

(2) the expected utilities of simulating the gas turbine engines range from 0.4 to 0.64.

The recommended course of action is to simulate the gas turbine engine at the Propulsion System LBTS. These results are consistent over the entire range of the utilities. The different shapes of the schedule attribute utility curve do not affect the solution results.

DECISION TREE MARK 92/2 FCS

ACTUAL EQUIPMENT AND NO EQUIPMENT BRANCHES

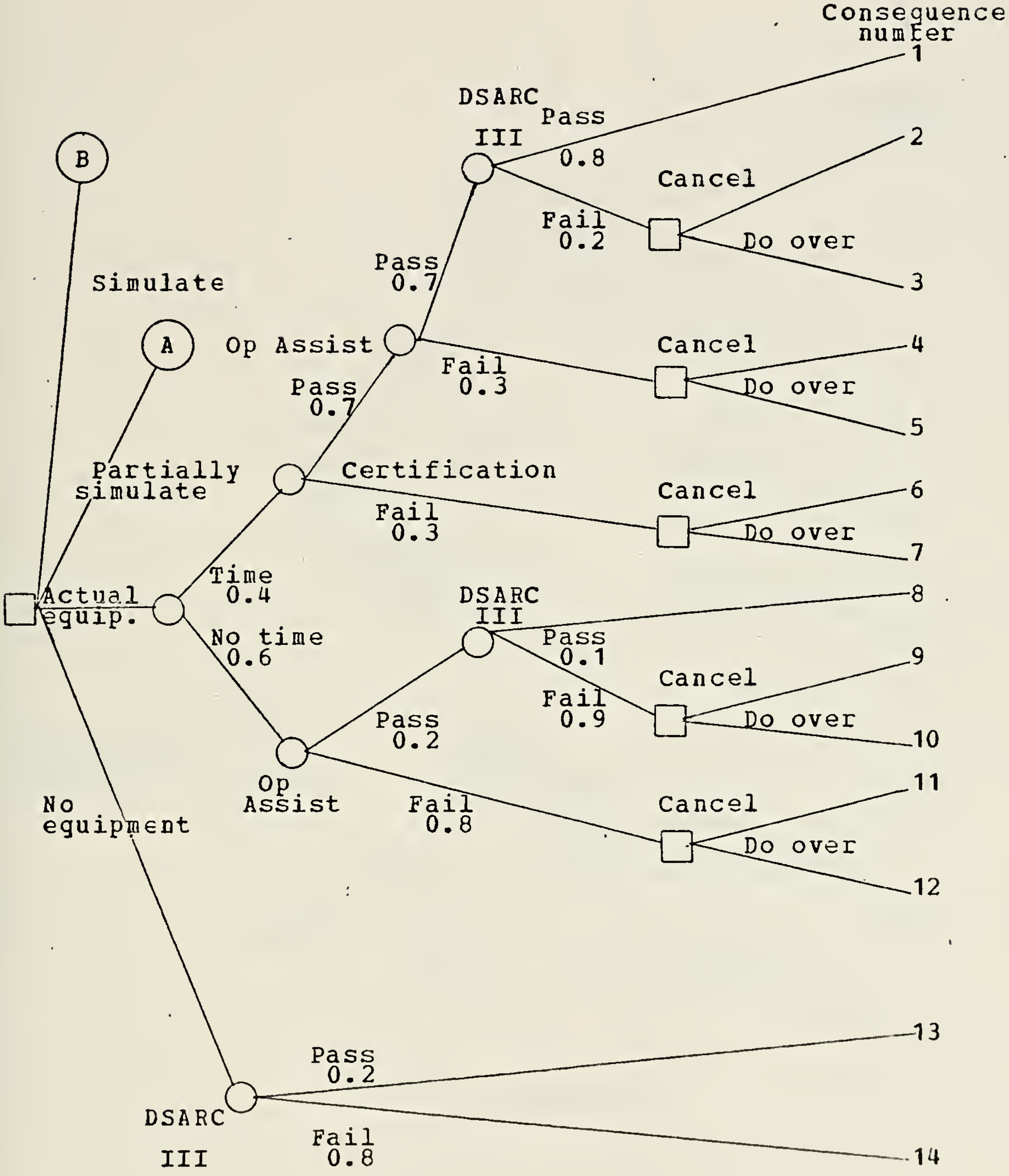



FIGURE 9

DECISION TREE MARK 92/2 FCS

PARTIALLY SIMULATE BRANCH

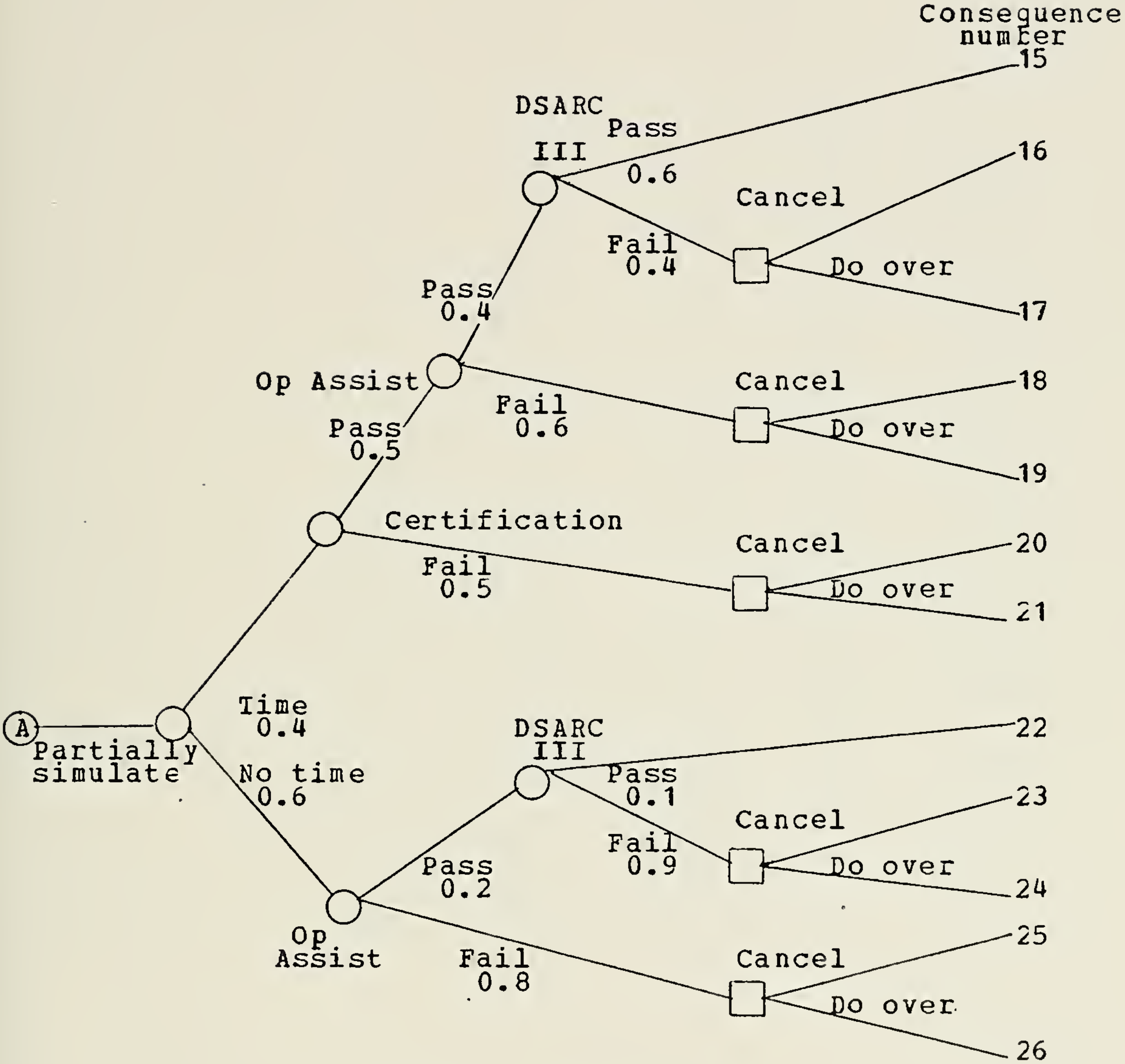



FIGURE 9 (continued)

DECISION TREE MARK 92/2 FCS

SIMULATE BRANCH

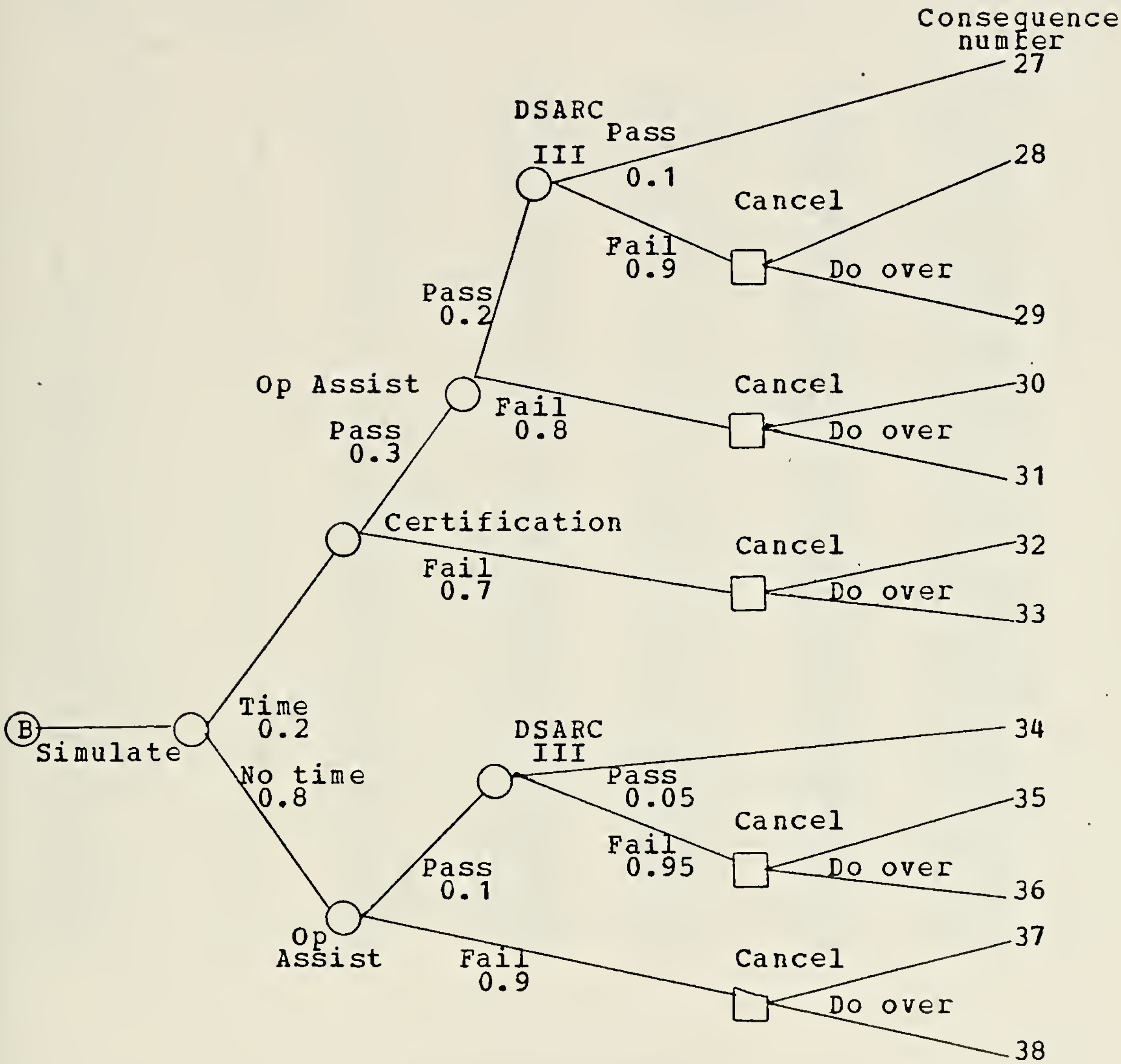



FIGURE 9 (continued)

TABLE IX

CONSEQUENCE NUMBER, OUTCOMES AND RESULTS

FCS DECISION TREE

| NR | OUTCOMES | | | UTILITY | | | |
|---|---|---|---|---|---|---|---|
| | Use | Sched | Cost | 1 | 2 | 3 | 4 |
| 1 | 3 | 1.5 | 13.5 | 0.81 | 0.81 | 0.81 | 0.81 |
| 2 | 0 | 1.5 | 18.5 | 0.42 | 0.42 | 0.42 | 0.42 |
| 3 | 3 | 6 | 18.5 | 0.29 | 0.42 | 0.55 | 0.59 |
| 4 | 0 | 6 | 18.5 | 0.08 | 0.21 | 0.34 | 0.38 |
| 5 | 3 | 6 | 18.5 | 0.29 | 0.42 | 0.55 | 0.59 |
| 6 | 0 | 6 | 18.5 | 0.08 | 0.21 | 0.34 | 0.38 |
| 7 | 3 | 6 | 18.5 | 0.29 | 0.42 | 0.55 | 0.59 |
| 8 | 3 | 6 | 13.5 | 0.47 | 0.60 | 0.73 | 0.77 |
| 9 | 0 | 6 | 18.5 | 0.08 | 0.21 | 0.34 | 0.38 |
| 10 | 3 | 6 | 18.5 | 0.29 | 0.42 | 0.55 | 0.59 |
| 11 | 0 | 6 | 18.5 | 0.08 | 0.21 | 0.34 | 0.38 |
| 12 | 3 | 6 | 18.5 | 0.29 | 0.42 | 0.55 | 0.59 |
| 13 | 0 | 0 | 0 | 0.99 | 0.99 | 0.99 | 0.99 |
| 14 | 3 | 6 | 18.5 | 0.29 | 0.42 | 0.55 | 0.59 |
| 15 | 2 | 1.5 | 9.5 | 0.93 | 0.93 | 0.93 | 0.93 |
| 16 | 0 | 6 | 12.5 | 0.74 | 0.74 | 0.74 | 0.74 |
| 17 | 2 | 6 | 12.5 | 0.48 | 0.60 | 0.73 | 0.77 |
| 18 | 0 | 6 | 12.5 | 0.29 | 0.42 | 0.55 | 0.59 |
| 19 | 2 | 6 | 12.5 | 0.47 | 0.60 | 0.73 | 0.77 |
| 20 | 0 | 6 | 12.5 | 0.29 | 0.42 | 0.55 | 0.59 |
| 21 | 2 | 6 | 12.5 | 0.47 | 0.60 | 0.73 | 0.77 |
| 22 | 2 | 6 | 9.5 | 0.58 | 0.71 | 0.84 | 0.88 |
| 23 | 0 | 6 | 12.5 | 0.29 | 0.42 | 0.55 | 0.59 |
| 24 | 2 | 6 | 12.5 | 0.47 | 0.60 | 0.73 | 0.77 |
| 25 | 0 | 6 | 12.5 | 0.29 | 0.42 | 0.55 | 0.59 |
| 26 | 2 | 6 | 12.5 | 0.47 | 0.60 | 0.73 | 0.77 |
| 27 | 1 | 1.5 | 7.5 | 0.92 | 0.92 | 0.92 | 0.92 |
| 28 | 0 | 1.5 | 7.5 | 0.81 | 0.81 | 0.81 | 0.81 |
| 29 | 1 | 6 | 12.5 | 0.40 | 0.53 | 0.66 | 0.70 |
| 30 | 0 | 6 | 12.5 | 0.29 | 0.42 | 0.55 | 0.59 |
| 31 | 1 | 6 | 12.5 | 0.40 | 0.52 | 0.66 | 0.70 |
| 32 | 0 | 6 | 12.5 | 0.29 | 0.42 | 0.55 | 0.59 |
| 33 | 1 | 6 | 12.5 | 0.40 | 0.52 | 0.66 | 0.70 |
| 34 | 1 | 6 | 7.5 | 0.57 | 0.70 | 0.83 | 0.88 |
| 35 | 0 | 6 | 12.5 | 0.29 | 0.42 | 0.55 | 0.59 |
| 36 | 1 | 6 | 12.5 | 0.40 | 0.53 | 0.66 | 0.70 |
| 37 | 0 | 6 | 12.5 | 0.29 | 0.42 | 0.55 | 0.59 |
| 38 | 1 | 6 | 12.5 | 0.40 | 0.53 | 0.66 | 0.70 |

SOLUTION RESULTS

| ALTERNATIVE | EXPECTED UTILITY | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| 1. Actual | 0.38 | 0.48 | 0.59 | 0.63 |
| 2. Partially simulated | 0.50 | 0.62 | 0.74 | 0.78 |
| 3. Simulated | 0.40 | 0.53 | 0.66 | 0.70 |
| 4. None | 0.43 | 0.53 | 0.64 | 0.67 |

DECISION TREE LM 2500 GAS TURBINE ENGINE
ACTUAL EQUIPMENT BRANCH

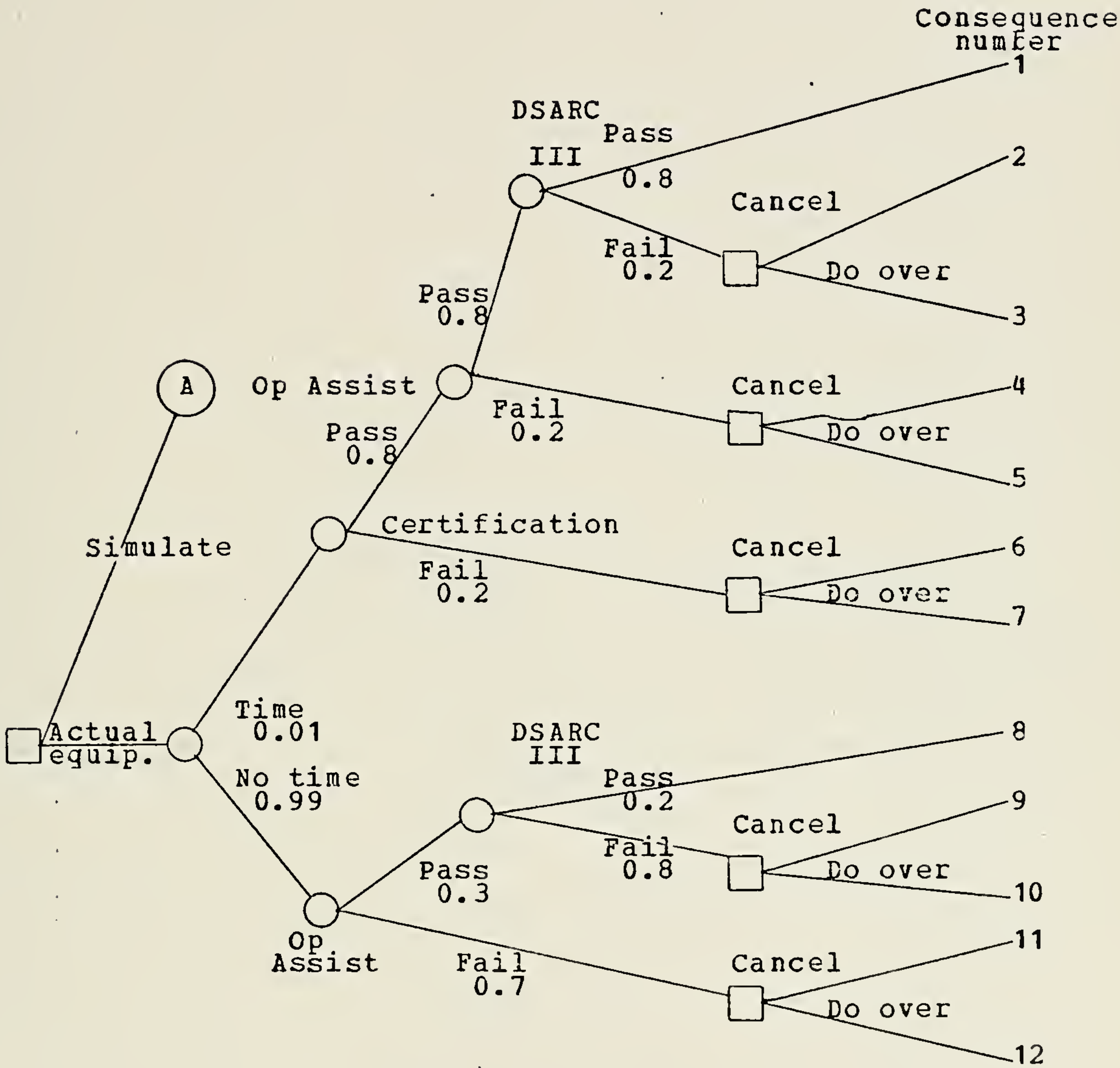



FIGURE 10

DECISION TREE LM 2500 GAS TURBINE ENGINE

SIMULATE BRANCH

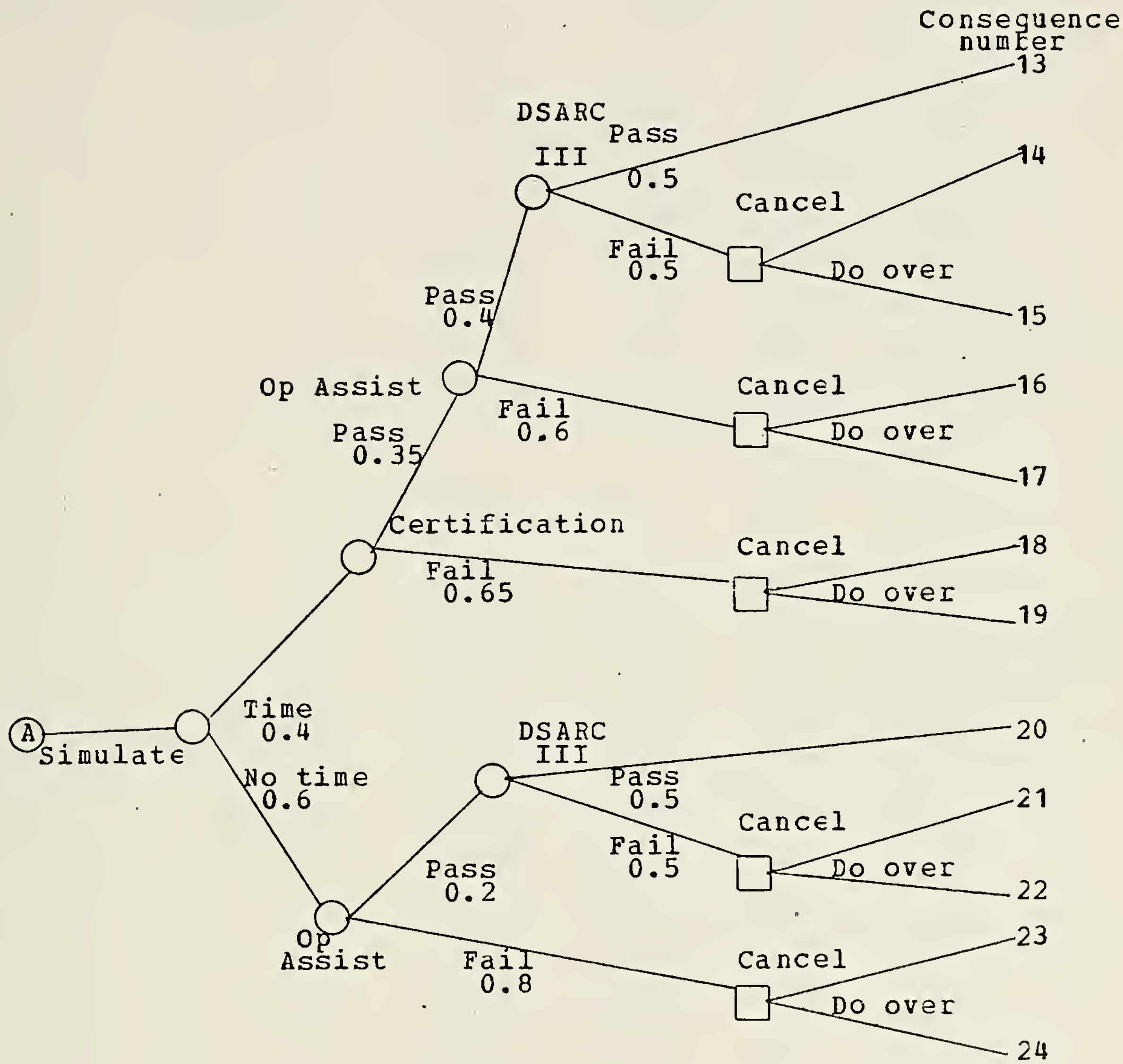



FIGURE 10 (continued)

TABLE X

CONSEQUENCE NUMBER, OUTCOMES AND RESULTS
GAS TURBINE DECISION TREE

| NR | OUTCOMES | | | UTILITY | | | |
|---|---|---|---|---|---|---|---|
| | Use | Sched | Cost | 1 | 2 | 3 | 4 |
| 1 | 3 | 10 | 14 | 0.51 | 0.51 | 0.51 | 0.51 |
| 2 | 0 | 16 | 15 | 0.11 | 0.14 | 0.20 | 0.25 |
| 3 | 3 | 16 | 15 | 0.19 | 0.22 | 0.29 | 0.35 |
| 4 | 0 | 16 | 15 | 0.11 | 0.14 | 0.20 | 0.25 |
| 5 | 3 | 16 | 15 | 0.19 | 0.22 | 0.29 | 0.35 |
| 6 | 0 | 16 | 15 | 0.11 | 0.14 | 0.20 | 0.25 |
| 7 | 3 | 16 | 15 | 0.19 | 0.22 | 0.29 | 0.35 |
| 8 | 3 | 16 | 14 | 0.22 | 0.25 | 0.31 | 0.38 |
| 9 | 0 | 16 | 15 | 0.11 | 0.14 | 0.20 | 0.25 |
| 10 | 3 | 16 | 15 | 0.19 | 0.22 | 0.29 | 0.35 |
| 11 | 0 | 16 | 15 | 0.11 | 0.14 | 0.20 | 0.25 |
| 12 | 3 | 16 | 15 | 0.19 | 0.22 | 0.29 | 0.35 |
| 13 | 1 | 10 | 3 | 0.82 | 0.82 | 0.82 | 0.82 |
| 14 | 0 | 16 | 4 | 0.38 | 0.42 | 0.50 | 0.57 |
| 15 | 1 | 16 | 4 | 0.43 | 0.47 | 0.55 | 0.63 |
| 16 | 0 | 16 | 4 | 0.38 | 0.42 | 0.50 | .57 |
| 17 | 1 | 16 | 4 | 0.43 | 0.47 | 0.55 | 0.63 |
| 18 | 0 | 16 | 4 | 0.38 | 0.42 | 0.50 | 0.57 |
| 19 | 1 | 16 | 4 | 0.43 | 0.47 | 0.55 | 0.63 |
| 20 | 1 | 16 | 3 | 0.46 | 0.50 | 0.58 | 0.66 |
| 21 | 0 | 16 | 4 | 0.38 | 0.42 | 0.50 | 0.57 |
| 22 | 1 | 16 | 4 | 0.43 | 0.47 | 0.55 | 0.63 |
| 23 | 0 | 16 | 4 | 0.38 | 0.42 | 0.50 | 0.57 |
| 24 | 1 | 16 | 4 | 0.43 | 0.47 | 0.55 | 0.63 |

SOLUTION RESULTS

| ALTERNATIVE | EXPECTED UTILITY | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| 1. Actual | 0.19 | 0.23 | 0.29 | 0.35 |
| 2. Simulated | 0.45 | 0.49 | 0.56 | 0.64 |

# VI. SUMMARY AND RECOMMENDATIONS

In this thesis, decision analysis methodology was applied to the problem of some project management trade-off decisions required for the Patrol Frigate Land Based Test Sites. In particular, the question of what PF subsystems should be installed and tested at the LBTS's was studied.

This chapter summarizes the content of the thesis, presents recommendations and provides suggestions for further research.

## A. THESIS SUMMARY

Chapter II provided the background of the Patrol Frigate Land Based Test Sites. The DSARC review process was introduced along with the required test and evaluation requirements necessary in each stage of the Patrol Frigate's acquisition cycle. The problem of what the composition of subsystems should be in the Combat and Propulsion System LBTS so that adequate test and evaluation with satisfactory results can be supplied to DSARC III, was provided as an example to which decision analysis methodology can be applied.

Chapter III supplied the decision analysis methodology required to formulate and solve the PF LBTS problem described in Chapter II. The steps in the formal process of decision analysis were discussed. They are:

(1) structuring the problem in terms of a decision tree,

(2) evaluation of the consequences in utility numbers,

(3) assignment of probabilities to the branches of the chance forks of the decision tree and

(4) determination of the optimal strategy by the "averaging out and folding back" process.

It was pointed out that the formal analysis is an iterative process. First, a broad description of the problem with rough assessments of the utilities and probabilities is made to determine whether any branches at decision forks can be eliminated or added. Next, the measurements are refined and certain forks added or eliminated. This cycle is repeated until there is satisfaction with the results of the analysis.

The decision tree represents the chronolcgical arrangement of the choices or alternatives controlled by the decision-maker and the choices determined by chance. The evaluation procedures for the assignment of utility numbers to each consequence were discussed. A consequence is represented by a path through the complete decision tree. The utility numbers are generated by a utility function which transforms or maps the attribute describing the outcome of a consequence into a scalar value. The consequences for a complex problem are generally described by multiple attributes which complicate the construction of the utility function. Simplification of the multiattribute utility function was discussed utilizing the properties of utility independence, pairwise preferential independence and pairwise marginality. Table I summarized the properties necessary for each type of utility function simplification. The assessment of the judgmental probabilities to each chance fork of the decision tree was then outlined. With all the necessary information available for the decision

tree analysis, the technique of "averaging out and folding back" to determine the expected utility of each alternative was described. The alternative with the greatest expected utility is chosen as the recommended course of action.

The Patrol Frigate LBTS problem was formulated in Chapter IV. This formulation encompassed the initial iteration of a formal decision analysis process. The Mark 92/2 fire control system, the AN/SPS-49 radar and the LM 2500 gas turbine engine were the PF subsystems examined. In the testing and evaluation process of these subsystems at the LBTS, the Project Manager worried about the installation and testing costs, the schedule for adequate test and evaluation, the uncertainty of passing DSARC III review and the usefulness of the subsystem at the LBTS to the program after DSARC III. His alternatives, in general, were to:

(1) install actual or simulated equipment at the LBTS,

(2) conduct at-sea testing of each subsystem during Operational Evaluations,

(3) monitor tests at the vendor's activity and at sea or

(4) conduct no further testing.

In passing DSARC III, the Project Manager is concerned with the uncertainty of passing Certification and Operational Assist prior to the DSARC III review. He is also uncertain as to the availability of time to accomplish these test requirements. These uncertainties were incorporated into the decision tree structure as chance forks in the appropriate order along the paths of the tree. The alternatives chosen for the fire control system were to install the actual equipment, partially simulate the fire control system, simulate all of the equipment or not to include the fire control system at the Combat System LBTS.

The alternatives chosen for the AN/SPS-49 radar were to install the actual equipment, simulate the radar system or not to include the radar at the Combat System LBTS. Two alternatives were chosen for the LM 2500 gas turbine engine. They were to install the engine or simulate the engine at the Propulsion System LBTS.

Cost, schedule and future usefulness were selected as the attributes describing the outcomes of each consequence of the tree. These attributes for the three subsystem problems were determined to have the properties of first order utility independence and pairwise preferential independence. As a result, the utility functions were expressed in the multiplicative form. The judgmental probabilities assessed for each chance fork are listed in Table VII.

With the decision tree structure defined, the utility functions derived and the chance fork probabilities assessed, each subsystem problem was structured in terms of a decision tree in Chapter V. A computer program, written in the BASIC language, was constructed to evaluate the consequences of the tree in utility numbers and to "average out and fold back" the tree to arrive at the expected utility of each alternative considered. Tables VIII, IX and X list the results. For the SPS-49 radar, the recommended alternative was not to install the radar at the Combat System LBTS. For the LM 2500 gas turbine engine, the recommended alternative was to simulate the engine at the Propulsion System LBTS. For the Mark 92/2 FCS, the recommended alternative was to partially simulate the fire control system.

## B. RECOMMENDATIONS

The decision tree analysis yielded several recommendations which contrast with the alternatives selected by the PF Project Manager. In actuality, it has been determined that the SPS-49 radar and the LM 2500 gas turbine are to be installed at their respective Land Based Test Sites [Ref. 5]. A result of this thesis is that the radar should not be installed and the gas turbine engine should be simulated. It is recommended that these alternatives should be further considered by the PF Project Manager. In the case of the SPS-49 radar, it is not too late to consider the alternative of not installing the subsystem at the LBTS. Installation of the LM 2500 gas turbine engines is already in progress and it is, perhaps, too late to consider its simulation. The alternative selected for the Mark 92/2 FCS was to partially simulate the fire control system which is in agreement with what was actually decided. This alternative, however, was primarily selected by the Project Manager because of the location of the Combat System LBTS where, out of necessity, the missile launchers and gun systems have to be simulated [Ref. 5].

The alternative of not installing the LM 2500 gas turbine at the LBTS was not considered in the analysis. If there is no engine, then there is no propulsion system. This alternative, if considered, really leads to the question of the desirability of a propulsion system LBTS. Rough data was available for consideration of the alternative of installing no engine and the expected utility of this alternative was computed. It was found that the expected utility was greater than that of the other two alternatives considered. This result would lead directly to the recommendation that a Propulsion System LBTS would not

be required. It is recommended that for future ship acquisition projects, the desirability of a propulsion system LBTS be closely studied. A propulsion system LBTS should not be preordained by the spirit of existing DOD Directives.

The analysis of this thesis has shown some results which are in contrast to the alternatives actually selected. This thesis has shown that decision analysis can be a viable decision-making tool for the project manager. It is a stimulus to think about new alternatives. It allows the decision-maker to scrutinize a problem as an organic whole. Decision analysis provides the decision-maker with the means to distinguish his preferences for consequences from his judgments about uncertainties [Ref. 11]. Decision analysis also allows the project manager to demonstrate that his decisions were not made on a casual basis and that a formalized decision approach was used. He can use the analysis to communicate the rationale of the chosen strategy to obtain support for his decision. It is recommended that decision analysis methodology be incorporated more fully into the project management environment. Raiffa [Ref. 11] states:

> "In my personal opinion, one part of the justification for adopting the methodology of decision analysis is that the underlying behavioral assumptions are appealing; a second part of the justification is that this methodology is an operational mode of analysis (at least for many problems, and the class is widening); and the final part of the justification is, what would you do otherwise?"

## C. SUGGESTIONS FOR FURTHER RESEARCH

This thesis represents an initial analysis of a complicated problem. Further research is necessary to

refine the probability and utility measurements. In particular, the effect of performance as an attribute should be further studied. This is a very complicated area and would make a thesis in its own right. The probability assessments were made at the project manager level. These probabilities could be further refined by assessing the judgments of technical personnel located at the LBTS and at the level of the Office of the Chief of Naval Operations. These assessments could then be compared and refined for the next iteration of the analysis.

The tools developed in this thesis can be applied to other areas of system acquisition program management. Some suggested areas are:

(1) an analysis of procurement contract alternatives of a major weapons system acquisition,

(2) an analysis of the different options in the selection of subsystems necessary for a ship or weapons system,

(3) an analysis of the alternatives among different types of hull platforms for a designated weapons system such as the AEGIS system and

(4) an analysis of a centralized procurement plan for material other than government furnished material versus the alternative of independent procurement of materials by several contractors for the same weapons system acquisition project.

## D. A CONCLUDING REMARK

It is hoped that this thesis has generated some interest

in decision analysis in the project management environment. The decisions required are complex and involve a great deal of uncertainty in an area where cost and schedule over-runs make it desirable that the option selected is the best possible. The Congress and concerned citizens demand it. Decision analysis is a tool that managers in the procurement of major weapons systems can use. The ideas of decision analysis are relatively new but they are too promising to ignore. Decision analysis can be experimented with by applying it to selected problems on paper and comparing the results with decisions that are actually made. If the results are favorable or raise some valid questions not considered, as in the example provided by this thesis, then these techniques should be adopted for use in the future.

## APPENDIX A

### SCALING CONSTANT EVALUATION MARK 92/2 FCS

The steps in evaluating the parameters of the utility function for the Mark 92/2 FCS decision tree are outlined in this appendix. This involves evaluation of the scaling constants K, $k_1$, $k_2$ and $k_3$ of the utility function

$$1 + Ku(\underline{X}) = \prod_{i=1}^{3} [1 + Kk_i u_i(x_i)].$$

Section B.3., Chapter IV, contains a description of this process.

### A. PREFERENCE RANKING OF ATTRIBUTES

The preferences for the three attributes were ranked by the PF Test and Evaluation Manager as: cost is preferred to schedule, and schedule is preferred to usefulness [Ref. 19].

### B. DETERMINATION OF LINEARLY INDEPENDENT EQUATIONS

To establish four linearly independent equations, equation (3), Chapter IV,

$$1 + K = \prod_{i=1}^{3} (1 + Kk_i)$$

and equation (4)

$$1 + m_j K = \prod_{i=1}^{3} (1 + Kk_i) / (1 + Kk_j),$$

are used. The utility value $m_j$, where j = 1,.,3, is first

determined by the assessment of gambles of the alternatives listed below.

| ALTERNATIVES | USEFULNESS (scalar) | SCHEDULE (month) | COST (million) |
|---|---|---|---|
| A | 3 | 1.5 | 7.5 |
| B | 0 | 1.5 | 7.5 |
| C | 3 | 6 | 7.5 |
| D | 3 | 1.5 | 18.5 |
| E | 0 | 6 | 18.5 |

The gambles are assessed per the following table:

| GAMBLE | UTILITY ($m_j$) |
|---|---|
| C is indifferent to <A,.7,E> | $m_2 = 0.70$ |
| D is indifferent to <C,.6,E> | $m_3 = 0.44$ |
| B is indifferent to <A,.6,E> | $m_1 = 0.88$ |
| C is indifferent to <B,.5,D> | $m_2 = 0.66$ |
| D is indifferent to <B,.5,E> | $m_3 = 0.44$ |
| B is indifferent to <A,.8,D> | $m_1 = 0.88$ |
| C is indifferent to <B,.8,E> | $m_2 = 0.70$ |
| D is indifferent to <A,.4,E> | $m_3 = 0.40$ |
| B is indifferent to <A,.9,E> | $m_1 = 0.90$ |

The utility of B, $m_1$, is selected as 0.88. The utility of C, $m_2$, is selected as 0.66. The utlity of D, $m_3$, is selected as 0.44.

## C. SOLUTION OF SCALING CONSTANTS

With $m_1$, $m_2$ and $m_3$ assessed, the scaling constant K can be determined from equation (6), Chapter IV,

$$(1 + K)^2 = \prod_{j=1}^{3} (1 + m_j K)$$

$$= (1+.88K)\ (1+.66K)\ (1+.44K).$$

Hence,

$$K\ (.26K^2+.26K-.02) = 0,$$

where K has the values 0, -1.08 and 0.07. Keeney [Ref. 13] shows that the value K which is nonzero and greater than -1 is chosen, therefore, K = 0.07 is selected.

Since the constant K is known, $k_1$, $k_2$ and $k_3$ can be determined from equation (7), Chapter IV,

$$k_j = (1 - m_j) / (1 + m_j K).$$

Therefore,

$$k_1 = (1 - .88) / [1 + .88(.07)]$$

$$= 0.21,$$

$$k_2 = (1 - .66) / [1 + .66(.07)]$$

$$= 0.42$$

and

$$k_3 = (1 - .44) / [1 + .44(.07)]$$

$$= 0.64.$$

## APPENDIX B

## SCALING CONSTANT EVALUATION SPS-49 RADAR

The steps in evaluating the parameters of the utility function for the SPS-49 radar decision tree are outlined in this appendix. This involves evaluation of the scaling constants K, $k_1$, $k_2$ and $k_3$ of the utility function

$$1 + Ku(\underline{X}) = \prod_{i=1}^{3} [1 + Kk_i u_i (x_i)].$$

Section B.3., Chapter IV, contains a description of this process.

### A. PREFERENCE RANKING OF ATTRIBUTES

The preferences for the three attributes were ranked by the PF Test and Evaluation Manager as: cost is preferred to schedule, and schedule is preferred to usefulness [Ref. 19].

### B. DETERMINATION OF LINEARLY INDEPENDENT EQUATIONS

To establish four linearly independent equations, equation (3), Chapter IV,

$$1 + K = \prod_{i=1}^{3} (1 + Kk_i)$$

and equation (4)

$$1 + m_j K = \prod_{i=1}^{3} (1 + Kk_i) \;/\; (1 + Kk_j),$$

are used. The utility value $m_j$, where j = 1,.,3, is first

determined by the assessment of gambles of the alternatives listed below.

| ALTERNATIVES | USEFULNESS (scalar) | SCHEDULE (month) | COST (million) |
|---|---|---|---|
| A | 3 | 1.5 | 1.5 |
| B | 0 | 1.5 | 1.5 |
| C | 3 | 4 | 1.5 |
| D | 3 | 1.5 | 3.5 |
| E | 0 | 4 | 3.5 |

The gambles are assessed per the following table:

| GAMBLE | UTILITY ($m_j$) |
|---|---|
| B is indifferent to <A,.9,E> | $m_1 = 0.90$ |
| C is indifferent to <A,.8,E> | $m_2 = 0.80$ |
| D is indifferent to <A,.5,E> | $m_3 = 0.50$ |
| B is indiffernt to <A,.5,c> | $m_1 = 0.9$ |
| C is indifferent to <B,.8,E> | $m_2 = 0.72$ |
| D is indifferent to <B,.5,E> | $m_3 = 0.45$ |
| B is indifferent to <A,.8,D> | $m_1 = 0.90$ |
| C is indifferent to <B,.7,D> | $m_2 = 0.78$ |
| D is indifferent to <C,.6,E>> | $m_3 = 0.48$ |

The utility of B, $m_1$, is selected as 0.9. The utility of C, $m_2$, is selected as 0.8 and the utility of D, $m_3$, is selected as 0.5.

## C. SOLUTION OF SCALING CONSTANTS

With $m_1$, $m_2$ and $m_3$ assessed, the scaling constant K can be determined from equation (6), Chapter IV,

$$(1 + K)^2 = \prod_{j=1}^{3} (1 + m_j K)$$

$$= (1+.9K)\ (1+.8K)\ (1+.5K).$$

Hence,

$$K\ (.36K^2+.57K+.2) = 0,$$

where K has the values 0, -1.06 and -0.52. Keeney [Ref. 13] shows that the value K which is nonzero and greater than -1 is chosen, therefore, K = -0.52 is selected.

Since the constant K is known, $k_1$, $k_2$ and $k_3$ can be determined from equation (7), Chapter IV,

$$k_j = (1 - m_j) / (1 + m_j K).$$

Therefore,

$$k_1 = (1-.9) / [1-.9(.52)]$$

$$= 0.19,$$

$$k_2 = (1-.8) / [1-.8(.52)]$$

$$= 0.34$$

and

$$k_3 = (1-.5) / [1-.5(.52)]$$

$$= 0.68.$$

## APPENDIX C

## SCALING CONSTANT EVALUATION GAS TURBINE ENGINE

The steps in evaluating the parameters of the utility function for the gas turbine engine decision tree are outlined in this appendix. This involves evaluation of the scaling constants K, $k_1$, $k_2$ and $k_3$ of the utility function

$$1 + Ku(\underline{X}) = \prod_{i=1}^{3} [1 + Kk_i u_i(x_i)].$$

Section B.3., Chapter IV, contains a description of this process.

### A. PREFERENCE RANKING OF ATTRIBUTES

The preferences for the three attributes were ranked by the PF Test and Evaluation Manager as: cost is preferred to schedule, and schedule is preferred to usefulness [Ref. 19].

### B. DETERMINATION OF LINEARLY INDEPENDENT EQUATIONS

To establish four linearly independent equations, equation (3), Chapter IV,

$$1 + K = \prod_{i=1}^{3} (1 + Kk_i)$$

and equation (4)

$$1 + m_j K = \prod_{i=1}^{3} (1 + Kk_i) \;/\; (1 + Kk_j),$$

are used. The utility value $m_j$, where j = 1,.,3, is first

determined by the assessment of gambles of the alternatives listed below.

| ALTERNATIVES | USEFULNESS (scalar) | SCHEDULE (month) | COST (million) |
|---|---|---|---|
| A | 3 | 10 | 3 |
| B | 0 | 10 | 3 |
| C | 3 | 16 | 3 |
| D | 3 | 10 | 15 |
| E | 0 | 16 | 15 |

The gambles are assessed per the following table:

| GAMBLE | UTILITY ($m_j$) |
|---|---|
| C is indifferent to <A,.5,E> | $m_2 = 0.5$ |
| B is indifferent to <A,.7,C> | $m_1 = 0.85$ |
| D is indifferent to <A,.3,E> | $m_3 = 0.3$ |
| C is indifferent to <B,.5,D> | $m_2 = 0.58$ |
| B is indifferent to <A,.7,d> | $m_1 = 0.82$ |
| D is indifferent to <C,.6,E> | $m_3 = 0.34$ |
| C is indifferent to <B,.6,E> | $m_2 = 0.51$ |
| B is indifferent to <A,.8,E> | $m_1 = 0.8$ |
| D is indifferent to <B,.4,E> | $m_3 = 0.34$ |

The utility of B, $m_1$, is selected as 0.85. The utility of C, $m_2$, is selected as 0.55 and the utility of D, $m_3$, is selected as 0.35.

## C. SOLUTION OF SCALING CONSTANTS

With $m_1$, $m_2$ and $m_3$ assessed, the scaling constant K can be determined from equation (6), Chapter IV,

$$(1 + K)^2 = \prod_{j=1}^{3} (1 + m_j K)$$

$$= (1+.85K)\ (1+.55K)\ (1+.35K).$$

Hence,

$$K\ (.16K^2-.04K-.25) = 0,$$

where K has the values 0, -1.11 and 1.37. Keeney [Ref. 13] shows that the value K which is nonzero and greater than -1 is chosen, therefore, K = 1.37 is selected.

Since the constant K is known, $k_1$, $k_2$ and $k_3$ can be determined from equation (7), Chapter IV,

$$k_j = (1 - m_j) \ / \ (1 + m_j K).$$

Therefore,

$$k_1 = (1-.85) \ / \ [1+.85(1.37)]$$

$$= 0.07,$$

$$k_2 = (1-.55) \ / \ [1+.55(1.37)]$$

$$= 0.26$$

and

$$k_3 = (1-.35) \ / \ [1+.35(1.37)]$$

$$= 0.44$$

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